Environmental Studies No.43

# The Use of Native and Agricultural Plant Species to Re-Vegetate Northern Mine Tailings

Canada

**Environmental Studies No.43**

# The Use of Native and Agricultural Plant Species to Re-Vegetate Northern Mine Tailings

Northern Affairs Program

T.C. Hutchinson
A.L. Kuja

Published under the authority of the
Hon. Bill Mcknight, P.C., M.P.,
Minister of Indian Affairs and
Northern Development,
Ottawa, 1988

QS-8401-000-EF-A1
Catalogue No. R71-19/43-1989E
ISBN 0-662-16736-X

©Minister of Supply and Services Canada

This Report was prepared under contract for the Northern Environment Directorate, Department of Indian and Northern Affairs.

The views, conclusions and recommendations expressed herein are those of the authors and not necessarily those of the Department.

90-04622/

© Minister of Supply and Services Canada 1989

Cat. No. R71-19/58-1989E

ISBN 0-662-16734-1

TABLE OF CONTENTS


| SECTION | PAGE NO. |
|---|---|
| ACKNOWLEDGEMENTS | iv |
| RESUME | v |
| 1. SUMMARY | 1 |
| 2. INTRODUCTION | 3 |
| 2.1 Tailings as an Environmental Problem | 3 |
| 2.2 Chemical Properties of Tailings | 3 |
| 2.3 Physical Properties of Tailings | 5 |
| 2.4 Biological Properties | 5 |
| 2.5 Conventional Agricultural Techniques | 6 |
| 2.6 Native Species vs Commercial Species | 7 |
| 3. OBJECTIVES AND APPROACH | 8 |
| 4. MATERIAL AND METHODS | 10 |
| 4.1 Collection and Preparation of Tailings | 10 |
| 4.2 Tailings Analyses | 10 |
| 4.3 Collection of Native Plant Material | 11 |
| 4.4 Glasshouse Experiments: Native Species Only | 11 |
| 4.5 Field Experiments on Native Species from Stressed Environments | 13 |
| 4.6 Field Experiments with Commercial Varieties | 13 |
| 5. RESULTS | 15 |
| 5.1 Chemistry of Tailings | 15 |
| 5.2 Glasshouse Experiments: Native Species Only | 16 |
| 5.2.1 Screening Experiment 1: Growth on Unamended Tailings | 16 |
| 5.2.2 Screening Experiment II: Growth on Amended Tailings | 18 |
| 5.2.3 Screening Experiment III | 19 |
| 5.3 Field Experiments on Native Species from Stressed Environments | 19 |
| 5.3.1 Unamended Tailings | 19 |
| 5.3.2 Amended Tailings | 19 |
| A) Cyprus Anvil Tailings | 19 |
| B) Arctic Gold and Silver Tailings | 20 |
| C) Venus Tailings | 20 |
| D) Whitehorse Copper Tailings | 20 |
| E) Nickel Rim Tailings | 22 |
| 5.3.3 Accumulation of Metals in Clonal Materials and Seedlings | 22 |
| A) Nickel Rim Tailings | 23 |
| B) Arctic Gold and Silver Tailings | 23 |
| C) Venus Tailings | 23 |
| D) Whitehorse Copper Tailings | 23 |
| 5.4 Field Experiments with Commercial Species | 23 |
| A) Arctic Gold and Silver Tailings | 23 |
| B) Venus Tailings | 24 |
| C) Whitehorse Tailings | 23 |

Table of Contents (con.)


| SECTION | PAGE NO. |
|---|---|
| 6. DISCUSSION | 26 |
| 6.1 Potential of Smoking Hills Species for Re-vegetation of Mining Areas | 26 |
| 6.2 Potential of Native Species for Re-vegetation of Mining Areas | 27 |
| 6.3 Local Transplants | 28 |
| 6.4 Effects of Amendments on Survival | 28 |
| 6.5 Performance of Commercial Species in the Field | 29 |
| 6.6 Effects of Tailings on Elemental Uptake of Vegetation | 30 |
| 6.7 Conclusions | 31 |
| 7. REFERENCES | 32 - 37 |
| 8. TABLES | 38 - 44 |
| 9. FIGURES | 45 - 50 |

## LIST OF TABLES


| TABLE | PAGE NO. |
|---|---|
| 1. Location and description of tailings. | 38 |
| 2. Combinations of species and amendments used in plots established in 1977 on tailings. | 39 |
| 3. Combinations of species and amendments used in plots established in 1978 on tailings. | 40 |
| 4. Measurements of pH, conductivity, bulk density, loss on ignition, particle size fractions and macronutrients in the tailings studied. | 41 |
| 5. Total concentrations of heavy metals and other potentially phytotoxic elements in the tailings studied. | 42 |
| 6. Concentrations of Pb, Zn, Cd, Cu, Ni and As in shoots and roots of six test species grown on unamended tailings in the glasshouse. | 43 |
| 7. Concentrations of As, Cd, Cu, Ni, Pb, and Zn in washed leaf and stem tissue of clonal material surviving on various amendments in the field. | 44 |


## LIST OF FIGURES


| FIGURE | PAGE NO. |
|---|---|
| 1. Growth response of *Artemisia tilesii*, *Arctagrostis latifolia*, *Deschampsia cespitosa* and *Hordeum jubatum* grown on each of the unamended tailings. | 45 |
| 2. Growth response of *Arctagrostis latifolia* and *Hordeum jubatum* grown in the glasshouse on amended tailings. | 46 |
| 3. Responses of plants to Nickel Rim tailings, unamended and amended. | 47 |
| 4. Relative vigor of clones transplanted from the Smoking Hills to various tailings. | 48 |
| 5. Seedling survivorship of *Deschampsia cespitosa* and *Hordeum jubatum* on tailings amendments at the Venus site. | 49 |
| 6. Seedling survivorship of *Deschampsia cespitosa* and *Hordeum jubatum* on tailing amendments at Arctic Gold and Silver and Whitehorse Copper. | 50 |

## ACKNOWLEDGEMENTS

We wish to thank D. Scanlon, B. Jefferies and J. Kaiser who have helped greatly in the field work and from time to time in the laboratory studies. W. Gizyn provided assistance in logistics at the Smoking Hills, N.W.T. The invaluable logistic support of the Polar Continental Shelf Project made transportation of people and vegetation from Smoking Hills to Whitehorse possible. In the Yukon, our thanks are due to Mr. Ken Gullen of DINA, as well as to Mr. N. Cornish of Cyprus Anvil Mines, Mr. D. Lindzay and Mr. R. Samuels of Whitehorse Copper Mines Ltd. Mr. R. Michelutti of Falconbridge Mines Ltd. helped in obtaining access to the Nickel Rim site.

The financial assistance of the Arctic Land Use Research Program of the Federal Department of Indian and Northern Affairs is gratefully acknowledged.

The editing for this final report and the compression of a 200 page report into 52 pages is due to the skill of Ms. Kersti Meema whose help is gratefully acknowledged.

This report is based on the Masters of Sciences Thesis of A.L. Kuja, University of Toronto. The total, comprehensive thesis is available through (1) The Indian Affairs Headquarters Library, (2) Regional Libraries of Yellowknife and Whitehorse (3) The Institute Library and (4) The National Research Council Library.

# UTILISATION D'ESPÈCES VÉGÉTALES INDIGÈNES ET COMMERCIALES POUR REPEUPLER DES TERRAINS DE RÉSIDUS MINIERS DU NORD

## 1. RÉSUMÉ

Dans cette étude, 5 espèces végétales indigènes ont été choisies dans deux environnements chimiques incléments (Smoking Hills, T. N.-O., et Sudbury, Ont.), au sol acide, à la pollution atmosphérique prononcée et avec de fortes concentrations de métaux dans le sol. Ces espèces végétales furent soumises à des essais pour évaluer leur capacité de survie et de croissance sur 8 terrains de résidus miniers, sensiblement différents, du Yukon, des Territoires du Nord-Ouest et du nord de l'Ontario. D'après les premiers résultats en serre, avec des résidus non amendés et d'autres traités à la chaux et aux engrais, 5 de ces terrains de résidus furent choisis, représentant une grande variété pour les essais d'espèces indigènes, ainsi que pour les essais de 8 herbes et d'une légumineuse vendues dans le commerce. Hordeum jubatum, un mauvaise herbe vigoureuse qui envahit les régions perturbées sub-arctiques, constituées de sols neutres à alcalins et très secs, faisait partie des expériences.

Les résidus pour ces essais furent analysés chimiquement. Plusieurs contenaient de grandes quantités de soufre, sous forme de sulfures, et leur potentiel de génération d'acide était extrêmement élevé. De plus, il y avait carence sérieuse des principaux agents nutritifs, particulièrement N et P. Certains renfermaient des concentrations très faibles de Ca, et souvent les rapports Ca : Mg n'étaient pas très favorables pour la croissance des plantes. Chaque résidu présentait une composition chimique différente, et tous renfermaient un ou plusieurs des éléments AS, Zn, Cu, Pb, Cd, W, Ni, Al, Fe et Mn, ce qui est révélateur d'une phytotoxicité probable. Le pH variaient de 1,8 à 9,1. Il y avait des périodes de sécheresse chaque année lors des essais sur le terrain, et elles étaient aggravées par le manque de matières organiques dans le sol et par la haute teneur en sable des résidus. Les amendements des résidus consistaient en addition de chaux aux terrains les plus acides pour élever le pH au-dessus de 5,0 et en additions de diverses combinaisons de tourbe et d'engrais. Un paillis de sciure fut utilisé sur la moitié des parcelles.

Les résultats de l'étude ont montré que, en dépit de la forte toxicité de la plupart des résidus utilisés, certaines des espèces indigènes présentent un potentiel intéressant pour le repeuplement dans le Nord. L'herbe Arctagrostis latifolia fut l'espèce qui a donné les meilleurs résultats. Les plantes provenant de clones de Smoking Hills et de Dempster Highway ont poussé sur des résidus non amendés pendant 6 saisons de croissance à Nickel Rim (pH 3,2), la multiplication et la floraison se poursuivant toujours. Elles ont également poussé sur les résidus non amendés de Whitehorse Copper (pH 9,1), pendant 4 saisons, jusqu'à leur recouvrement accidentel par plusieurs pieds de résidus frais. Sur les résidus d'Arctic Gold & Silver (ph 1,8), A. latifolia n'a pu survivre qu'après addition de chaux aux parcelles, la croissance s'effectuant normalement par la suite. Les spécimens de Dempster accusèrent également une croissance normale dans ces conditions. A Venus, A. latifolia a survécu sur des sols plus humides après amendement ou addition de tourbe. Ce n'est qu'à Cyprus Anvil que cette espèce n'a pu survivre, quels que furent les amendements employés. Cela était vrai aussi pour toutes les autres espèces soumises aux essais.

Aucune des autres espèces de Smoking Hills n'a semblé convenir au repeuplement des résidus. Hierochloe alpina et Carex bigelowii n'étaient pas assez tolérants vis-à-vis des acides et des métaux, et ces espèces ne supportaient pas du tout la sécheresse. Artemisia tilesii a bien supporté les diverses contraintes, mais elle se présente sous forme de touffes et ne se répand pas facilement. Elle était moins tolérante sur le terrain que A. latifolia.

Sur les résidus neutres à alcalins, l'herbe Hordeum jubatum, poussant à partir de graines, a connu une meilleure croissance sur tous les terrains que n'importe laquelle des autres espèces utilisées. Il n'y eut aucune inhibition causée par les fortes concentrations de métal dans les résidus, et elle a survécu à de grandes sécheresses. A la fin des essais, elle s'était multipliée par les germes jusqu'à Venus et Whitehorse. C'est une espèce qui envahit naturellement les zones de résidus dans la majeure partie de l'Amérique du Nord.

Il était assez surprenant qu'une population tolérant les métaux, Deschampsia cespitosa, de Sudbury, plantée sous forme de graines, connaisse une croissance médiocre sur les terrains d'Arctic Gold & Silver. Par contre, la croissance de l'espèce se fit bien sur les terrains amendés à la chaux de Nickel Rim, et mieux encore sur les terrains plus humides de Venus.

Des diverses espèces commerciales utilisées sur le terrain, 5 se révélèrent particulièrement utiles. Le brome inerme (Bromus inermis) fut la plus résistante de toutes, révélant une remarquable tolérance face à la rareté de l'eau et à une vaste gamme de pH. L'ivraie vivace (Lolium perenne), le vulpin des prés (Alopecurus pratensis), la fétuque élevée (Festuca arundinacea), et l'agropyre allongé (Agropyron elongatum) se sont toutes bien comportées sur plusieurs des terrains. mais de fortes quantités de chaux se sont révélées nécessaires sur les résidus acides. Pour presque toutes les espèces, l'ensemencement d'automne a semblé donner de meilleurs résultats que celui d'été ou de printemps.

Qu'il s'agisse d'espèces indigènes ou commerciales, l'addition de chaux et d'engrais s'est révélée indispensable pour beaucoup d'entre elles sur les résidus acides. Les espèces commerciales ont donné de bons résultats avec l'addition de N et P. Dans le cas des espèces indigènes, un engrais organique contenant 6-8-6-% de N, P et K en fraction soluble fut le plus efficace de tous. Pour les espèces commerciales, les fractions 10-20-10 et 21-7-14 ont été souvent aussi bonnes ou meilleures. L'addition de tourbe s'est révélée généralement bénéfique sur les résidus neutres et alcalins, mais défavorable sur les résidus acides, car il y avait alors augmentation de l'acidité.

Toutes les espèces plantées sur les résidus ont revélé une absorption importante d'éléments toxiques par les racines, lorsque ces élément étaient présents en fortes concentrations dans les résidus. Certains éléments, comme Zn, Ni, Cd et As, s'accumulaient également dans les pousses. Le mode d'absorption des éléments était très différent d'une espèce à l'autre.

## 1. SUMMARY

In this study, five native plant species were selected from two harsh chemical environments (Smoking Hills, N.W.T. and Sudbury, Ont.) which have acidic soils and heavy atmospheric pollution, as well as elevated soil metal levels and these plants were tested for their ability to survive and grow on 8 markedly different mine tailings from the Yukon, Northwest Territories and northern Ontario. From initial glasshouse trials on unamended tailings and on limed, fertilized tailings, five tailings sites were selected which represented a wide range of chemical and physical conditions. These were then used as field sites for trials of the native species, and for trials of 8 commercially used grasses and one legume. Hordeum jubatum, a vigorous weedy grass which colonizes disturbed areas in the sub-arctic on neutral to alkaline soils and under drought conditions, was included in the experiments.

The tailings tested were chemically analysed. Many contained large quantities of sulphur, as sulphides, and had tremendous acid generating potential. In addition, they were very deficient in major nutrients, especially N and P. Some had very low Ca levels as well as unfavourable Ca:Mg ratios for plant growth. Each tailing was chemically unique and all had concentrations of one or more of As, Zn, Cu, Pb, Cd, W, Ni, Al, Fe and Mn which was likely to prove phytotoxic. The pHs ranged from 1.8 to 9.1. Droughts occurred in each year of the field trials, accentuated by the lack of soil organic matter and by the high sand content of the tailings. Amendments were made to the tailings by addition of lime to acidic ones to raise the pH > 5.0 as well as additions of various combinations of peat and fertilizers. A sawdust mulch was used for half of the plots.

The results of the study indicated that, despite the high toxicity of most of the tailings used, some of the native species tested have a high potential for re-vegetation work in the north. The grass Arctagrostis latifolia was the most successful colonizer overall. Plants from clonal Smoking Hills and Dempster Highway populations grew on unamended tailings for 6 growing seasons at Nickel Rim (pH 3.2) and are still spreading and flowering. They also grew on Whitehorse Copper (pH 9.1) unamended tailings for 4 seasons until it was accidentally covered by several feet of fresh tailings. On Arctic Gold and Silver tailings (pH 1.8), A. latifolia only survived when lime was added to the plots, but it was then able to grow well. The Dempster plants also grew well in these conditions. At Venus A. latifolia survived on wetter areas when unamended or with peat added. Only at Cyprus Anvil did it fail to survive, irrespective of amendments used. This was also true for all other species tested.

None of the other Smoking Hills species appeared to be suitable for tailings work. Hierochloe alpina and Carex bigelowii were insufficiently acid- and metal-tolerant, and were also not drought-tolerant. Artemisia tilesii was quite tolerant to the various stresses, but has a tussock form and does not vegetatively spread readily. However, it also showed less tolerance in the field than A. latifolia.

On neutral to alkaline tailings, the grass Hordeum jubatum, raised from seed grew better on such sites than any of the other species used. It was not inhibited by high metal concentrations in the tailings and survived severe droughts. When experiments were terminated it was spreading by seed at Venus

and at Whitehorse. It is a natural colonizer of waste areas in much of North America.

It was surprising that the metal-tolerant population of Deschampsia cespitosa from Sudbury, when grown from seed, did not do well at the Arctic Gold and Silver site. It did, however, grow well on lime-amended sites at Nickel Rim, and established very well on the wetter sites at Venus.

Of the commercial varieties used in the field, five appeared particularly useful. Bromegrass (Bromus inermis) was the best overall, showing tolerance of low water availability and also of a wide range of pH. Perennial rye grass (Lolium perenne) , meadow foxtail (Alopecurus pratensis), tall fescue (Festuca arundinacea), and tall wheatgrass (Agropyron elongatum) all did well at several of the sites, though heavy liming was essential on the acidic tailings. Fall seeding for almost all species seemed to give better results than summer or spring seeding.

For both native and commercial species, lime and fertilizer additions appear to be imperative for many species on acidic tailings. The commercial species responded well to N and P additions. For the native species, the organic fertilizer with its 6-8-6% N:P:K soluble fraction was best overall. For commercial species often 10-20-10 and 21-7-14 were as good or better. Peat additions were generally beneficial on neutral and alkaline tailings but harmful on acidic ones as they enhanced the acidity.

All species grown on tailings showed substantial uptake of the toxic elements into roots if these elements were present in high concentrations in the tailings. Some elements such as Zn, Ni, Cd and As also accumulated in the shoots. Species differed markedly in their patterns of uptake for the elements.

## 2. INTRODUCTION

### 2.1 Tailings as an Environmental Problem

At present, in Canada, there are thousands of hectares of land that are buried under mine tailings as a result of the extraction and milling of metalliferous ores (e.g. Michelutti 1974). Ore grades in older mines are declining and the amount of tailings that must be discharged grows exponentially each year (Andrews 1977). There is a concern for the environmental and aesthetic damage caused by these tailings. Some of the oldest abandoned tailings in the Yukon and Northwest Territories are still devoid of vegetation some 60 years after operations closed, and studies have shown that unassisted re-vegetation, by invasion of native species, will not occur in the short-term (e.g., Bayne 1975). Assisted re-vegetation of tailings in these northern areas may be more difficult to achieve than in southerly latitudes because of the short growing season, extremely low temperatures, and often dry conditions in the arctic and subarctic regions (Peterson and Peterson 1977). On non-toxic mine waste sites, in contrast, rapid re-vegetation has often occurred in temperate regions.

Tailings are not soils and it is no simple matter to overcome the various chemical and physical conditions that exist in order that re-vegetation can be accomplished successfully. Tailings consist of finely ground rock which remains after the desired minerals are removed from the ore in the milling process.

Tailings are often disposed of in steep-sloped, mechanically unstable piles which have a potential to slip (Hardy 1977). Dykes built around tailings ponds are susceptible to gullying by water erosion, as well as to structural failure if poorly designed, causing release of tailings which can contaminate the adjacent areas, especially down-stream marshes, rivers and lakes (Andrews 1977). Re-vegetation stabilizes dykes and tailings, reducing the potential for erosion and collapse.

Unlike tailings, soils are made up of three components: a mineral mass containing plant nutrients derived from the breakdown of the parent material; an organic mass, some of which is in the form of humus, and a living component which includes micro-organisms. Not only do tailings initially lack these components, they also have many properties that inhibit plant growth. Moreover, each tailing must be dealt with individually because of its unique physical and chemical characteristics which strongly affect revegetation.

### 2.2 Chemical Properties of Tailings

Often the amelioration of the chemical properties of tailings is crucial to re-vegetation success. Elevated metal levels, acidity and deficiency of macronutrients are major factors to be overcome. All tailings from metalliferous ores con ain some metals (e.g., Al, Mn, Fe, Cr, Cu, Ni, Pb, Cd, Zn). Elevated levels of heavy metals can occur because extraction techniques in the milling process fail to completely extract desirable (saleable) elements and because the desired element may be in very low quantities compared with undesirable, toxic elements associated with the ore.

Many heavy metal ions at very low concentrations in solution are potentially phytotoxic (Bowen 1966). Many are substitutes for co-enzymes, thus producing non-functional protiens. Others inhibit or interfere with DNA and RNA replication. They can inhibit root elongation and cause Fe-induced chlorosis because they interfere with iron mobility and metabolism in roots, thus preventing iron being available for chlorophyll synthesis in leaves (e.g., Hewitt 1948; Wilkins 1957). The solubility of many metals (e.g., Al, Mn, Fe) increases significantly with increasing acidity (pH < 4.0) (Coleman and Thomas 1967; Buckman and Brady 1970). The availability of most heavy metals for plant uptake is thus greater in tailings with pH < 4.0 than tailings with neutral or basic pH (Peterson and Nielson 1973). However, in non-acid tailings, total concentrations of various heavy metals may attain such high levels that even the soluble portion is toxic to most plants. Furthermore, salts of a few elements such as Mo, B, As, and Se may increase in solubility at higher pH.

Most soils range in pH from 4.5 to 8.0 (Buckman and Brady 1970), with few plant species able to tolerate a pH less than 4.0 (Jackson 1967). The high concentration of free $H^+$ ions generated in the oxidation of sulphide tailings can injure plants and physiologically impair their absorption of Ca, Mg and P (Rorison 1972).

In addition to acid generation, a hard "ferrunginous cap", or 'iron pan', impervious to root penetration, can occur on pyritic tailings as hydrated ferric oxides and ferric sulphates are concentrated at the tailing surface as a result of surface evaporation and capillary action (Michelutti 1974).

Low levels of the macronutrients, nitrogen and phosphorus, can be an additional problem for the establishment of vegetation on tailings (Peterson and Nielson 1973). Most plants are adapted to take up nitrogen as nitrate rather than ammonium, but the latter is the predominant N form in acidic environments. Since N is completely absent in bedrock (Delwiche 1970), little or no N is present in tailings. Nitrogen in soils is primarily a result of long-term biological action during soil development. The autotrophic soil bacteria, Nitrosomonas and Nitrobacter, which are largely responsible for nitrification of ammonia to nitrite and nitrite to nitrate, function very poorly at the low pH's which occur in acid tailings (Rorison 1972) and many strains of Rhizobia (nitrogen-fixing nodule bacteria) cannot survive at pH < 4.0 (Jackson 1967).

Phosphorus is absorbed by plants as inorganic phosphate ions and is often in limited supply in soils at both low and high pHs (Buckman and Brady 1970). In acid tailings, Fe, Zn, and Al ions react with P to form insoluble phosphate precipitates which interfere with P uptake by plants. Phosphorus can also be immobilized as highly insoluble forms of calcium phosphate or absorbed by ferric hydroxide in alkaline tailings (Gemmell 1977). All of these processes lead to chronic phosphorus shortage in the plants growing on the tailings, causing stunted growth, shallow roots and a marked susceptibility to droughts and winter killing factors such as frost heaving.

Potassium, which is required by plants in large amounts, is retained in material with a high cation exchange capacity such as clays, but is easily leached from coarse material, especially in acidic tailings.

Calcium and magnesium are both utilized in large amounts by plants but are very soluble at low pH and are easily leached from acid tailings. In such tailings calcium and magnesium deficiencies can readily occur.

Generally, sulphur accounts for 0.2 - 0.7% of the biomass (dry weight) of plants. Sulphur is present at very high concentrations in pyritic tailings, generally as sulphite and elemental sulphur. However, these forms are not directly available to plants as they are highly insoluble. They can be made available to plants by conversion to the more water-soluble sulphate form by bacterially-assisted oxidation. The sulphur requirements of plants are usually met by moderate levels of sulphates in solution. On acid mine tailings, excessive sulphate levels often occur, which can reduce plant growth *per se* (Chapman 1966).

## 2.3 Physical Properties of Tailings

Many of the physical characteristics of tailings can inhibit the establishment of vegetation, i.e., instability, texture, lack of organic matter, susceptibility to drought, high surface temperatures, surface evaporation, etc. (Bradshaw *et al.* 1978).

Extremes in the texture of tailings is a factor affecting plant growth. Fine textured tailings, consisting of clay-like particles (<0.002 mm diameter) in tightly packed aggregates, result in low permeability and slow infiltration by water (e.g., Murray 1971). Poor aeration is also a factor that decreases growth on fine textured tailings (Ayerst 1978). Many tailings are of a sandy nature (< 0.5 mm diameter), porous, and have low moisture holding and cation exchange capacities. This allows nutrients to be leached from the material (Knabe 1965).

A common characteristic of all tailings is that they lack organic matter (Weston 1973). Re-vegetation, therefore, requires the addition of some form of organic material to compensate for the lack of cohesion of large particles, while it improves moisture retention and cation exchange capacity in sandy tailings. Organic matter can increase aeration between particles in fine textured tailings, and it can chelate phytotoxic ions, taking them out of the soil solution, and thus reducing their availability for plant uptake (Turner 1968, Walton 1973).

Germination and seedling establishment can be limited by the high temperatures which occur on tailings (Ogram and Fraser .978) and by surface evaporation which can result in a crust of metal salts, such as lead sulphate (Pitcairn 1969). Such surface metal levels may be much greater than in the original discharged tailings. In non-vegetated tailings the direct evaporation and formation of surface salt pans can lead to saline conditions favouring invasion by salt-tolerant species. In Ontario, salt-marsh species such as the grass *Puccinellia distans* have been recent, successful invaders of gold and silver mine sites at Timmins and Kirkland Lake.

## 2.4 Biological Properties

Tailings usually lack the essential fungal species and reservoir of spores necessary for the formation of mycorrhizae with roots. Mycorrhizae are less common on sandy soils which, like tailings, are low in organic matter (Kruckelmann 1974). Mycorrhizal fungi fail to form symbiotic associations in high temperatures (Marx *et al.* 1970) and in the presence of elevated levels of heavy metals (Harris and Jurgensen 1977) and sulphur (Bowen 1966).

## 2.5 Conventional Agricultural Techniques

Much of the work concerning tailings re-vegetation has involved attempts to amend tailings to meet the requirements of commercial (agricultural) species which have high nutrient demands and are neither acid- nor metal-tolerant. Conventional agricultural methods, such as liming, fertilizer application, mulching, and hydro-seeding, have been successfully utilized in re-vegetating non-toxic disturbed sites such as pits and quarries, strip-mined land and pipeline corridors (Murray 1974; Peterson and Peterson 1977; Marshall 1979; CLRA 1979). These techniques have been applied to tailings in Canada but results have often been costly and unsatisfactory, especially at toxic sites.

Tailings can have very high acid generation potential and thus very high liming requirements; from 25 to 180 tons per hectare on pyritic Cu tailings (Watkin 1978). Calcite ($CaCO_3$) or dolmitic limestone ($CaMg(CO_3)_2$), the latter having a high Mg content, are preferred over lime (CaOH) which is corrosive (Lundberg et al. 1977). The ongoing acid generation is a problem and unless the full impact of this is recognized, limed tailings can revert to extremes of acidity quite rapidly. For example, sufficient lime can be incorporated into the top 10-15 cm of the tailings to neutralize the acidity present, and thus allow an extremely good establishment of plants that year, only for the generation of new acidity to push the pH very low causing the death of all the plants in the subsequent year.

Fertilizers must be applied to tailings at rates far exceeding those recommended for agricultural soils because of the low nutrient status of tailings (Laughlin et al. 1973). Expensive, slow release fertilizers are often used to minimize nutrient loss due to leaching in coarse-textured tailings (Klock et al. 1975).

Applications of sewage sludge have been made to increase nutrients, as well as to provide organic matter for higher moisture holding and cation exchange capacities (Berry and Marx 1977), but these usually contain high metal levels.

Mulches are used to decrease extremes in diurnal temperature flux and to reduce water loss by evaporation. Various materials have been utilized for this purpose (e.g., straw, hardwood, sawdust, burlap strips, peat and sewage sludge), with varying success (Stover 1973, Heede 1975, Emanual 1976).

Attempts have been made to cover toxic tailings with a soil over-burden (Day et al. 1977). However, acidification of the soil layer above the buried pyritic tailings can occur (Pionke and Rogowski 1969). Soluble metals can move by capillary action from the toxic substrate beneath the amended layer into the rooting zone of the vegetative cover (Smith and Bradshaw 1972).

Conventional seed mixtures of perennial grasses and legumes are often used to obtain a stabilizing cover (Lesko et al. 1975). Legumes provide a self-sufficient nitrogen supply for the tailings due to the nitrogen-fixing bacteria in their root nodules. Herbaceous legumes are, however, susceptible to metal toxicity at low pH and metal tolerance in legumes is rare (Johnson et al. 1977).

The costs of re-vegetating tailings by agricultural techniques can be high, e.g., $6,200 per hectare for uranium tailings (Murray and Moffett 1977). Direct seeding of tailings using commercial varieties of grasses and legumes

are frequently unsuccessful even when fertilizers, soil overburdens, additions of organic matter and sophisticated methods of seed-bed preparation and hydroseeding are applied.

Sudden declines in growth can occur four or five years after initial treatments were made, due to a loss of fertility brought about by the depletion of nutrients by plant utilization and leaching (Johnson et al. 1977). Commercial species grow rapidly, and because of their high nutrient demands, require reapplication of fertilizers in order to maintain growth. Also, recycling of nutrients in tailings is low because of insufficient microbial activity necessary to decompose plant litter (Gemmel 1977). Accumulation of an impervious organic mat over a number of years due to inadequate soil microflora is a problem on even fairly successful re-vegetation schemes.

## 2.6 Native Species vs. Commercial Species

One goal of tailings re-vegetation in Northern Canada should be to encourage the return of the original flora through the use of native plants, especially pioneer species (Johnson and VanCleve 1976), since this provides an environmentally sound and low-cost management solution. Invasion by native species will be hindered if commercial species have been introduced because they can out-compete native species when high rates of fertilizer are applied (Younkin 1973; Grime 1973 a,b; Dabbs 1974). However, Brown and Johnson (1976) compared the performance of native and introduced seed mixtures at an alpine mine site in Montana and found that native species survived better and produced a denser ground cover than agricultural grass or legume varieties. Transplants did even better.

The advantages of using native plants for revegetation are that (1) they are adapted to poor nutrient conditions (Antonovics et al. 1967), (2) they are hardy against cold temperatures and less susceptible to frost damage than fast-growing commercial species (McCown 1972, 1973; Wielgolaski 1975), and (3) seeds from native species present a wide range of genetic variability (Antonovics et al. 1967; Johnson and VanCleve 1976).

The lack of an available seed source for large scale use is a disadvantage of using native species (Sutton 1975). Native perennial species are poor seed producers, especially in northern climates where species have adapted to asexual underground reproduction (Grime 1974; Wielgolaski 1975). Furthermore, native perennial species generally grow slowly. However, in toxic tailings this slow growth can be an advantage, in that it enables them to survive because of slower uptake and metabolism of toxic elements and a lower demand for scarce essential elements compared with the commercial species with higher growth rates and nutrient demands.

Much of the information about the potential of native species for tailings re-vegetation was derived from studies of natural succession in disturbed sites in arctic, subarctic and boreal regions. Native pioneer species such as the grasses Calamagrostis canadensis, Arctophila fulva, Poa arctica, Luzula confusa and cotton grass Eriophorum vaginatum are all successful invaders of mesic disturbed sites, whereas Eriophorum scheuchzeri, the sedge Carex aquatilis and the composite Senecio congestus are invaders of wetter sites (Hernandez 1972, 1973). The potential of various grasses (e.g., Arctagrostis latifolia, Calamagrostis canadensis, Poa lanata, Hierochloe alpina, and H.

odorata) for invading disturbed sites has been studied (Mitchell 1974, and others).

Shrubs and trees may be more effective than grasses and legumes for stabilizing tailings because they produce deeper and more extensive root systems and may also be more effective in attracting and sheltering wildlife. Species such as willows, poplars, birch and alder have low nutrient requirements (Sheldon and Bradshaw 1976). Poplars and willow can be easily propagated from viable root stocks (Zsuffa 1971; Laidlaw 1974). Woody plants could provide nuclei for invasion of herbaceous species that might germinate in the litter accumulated under the trees and shrubs (Yarranton and Morrison 1975; Miller 1978). Natural seedling-in of birch (Betula papyrifera) has occurred on a wide scale at the Copper Cliff, INCO, tailings site, and on old tailings at Larder Lake, Ontario, where even jack pine (Pinus banksiana) and balsam fir (Abies balsamea) have invaded.

## 3. OBJECTIVES AND APPROACH OF THE PRESENT STUDY

The objectives of this study were as follows:

A) To screen selected native species obtained from areas of natural or anthropogenic stress for their usefulness in the re-vegetation of difficult (very toxic) northern tailings sites. High acidity and salinity, heavy metal concentrations and drought were the major stress factors considered.

B) To compare the performance of these native species with that of selected agricultural-conventional varieties commonly used in hay mixtures or in tailings re-vegetation work.

C) To chemically and physically characterize the tailings used for field trials and glasshouse experiments to determine the likely problems they present for plant growth.

D) To assess the potential of various soil amendments, such as liming, fertilizer combinations and organic addition, for use in re-vegetation of difficult tailings sites.

E) To determine the chemical (elemental) composition of roots and shoots of the test species when grown on the various tailings, in order to relate elemental uptake to survival and performance, and to soil concentrations (availability). This is of importance in assessing potential problem for wildlife through grazing on re-vegetated sites.

Native plants were collected from the Smoking Hills area of Cape Bathurst, N.W.T. and Sudbury, Ontario. These two areas are subject to either major natural or anthropogenic pollutant stresses. In the Smoking Hills area, sulphur fumigations are produced by the spontaneous burning of exposed strata of bituminous shales along a section of seacliff (Yorath et al. 1975). Studies by Hutchinson et al. (1978) showed that the soil in the zone subjected to frequent fumigations ($SO_2$ and $H_2SO_4$ aerosols) is very acidic with a pH of 2.0 to 3.0, compared with normal tundra soils in this area with a pH of 7.0 to 7.5. The extremely low pH of the soil has mobilized metals (e.g., Al, Mn, Fe, Zn) and has caused leaching of bases (Ca, Mg, Ba and K). Volatile elements

(e.g., As, Sb, Ba, V, Se and elemental S) are being emitted into the air from the baking bituminous shales (Gizyn 1980). Precipitation at the Smoking Hills is less than 14 cm per year and when it occurs in the fumigated areas, results in extremely acidic rain or snow (pH < 3.0). Despite the harsh conditions, a number of plant species are found growing close to the fumigation source. It is likely that these plant populations have undergone natural selection for various tolerances (i.e., acid-and-multi-elemental tolerance) and such native, arctic species might have great potential for revegetating nothern mine tailings as they are at least already climatically adapted.

A second source of native species of potential value in tailings re-vegetation work is from the area around Sudbury, Ontario, which has been heavily polluted by smelters and acidic $SO_2$ fumes for 80 years. Air-borne particulates containing Ni, Cu, Fe, and Co have accumulated extensively in the soils (Hutchinson and Whitby, 1974, 1977) while much of the surface soil within a few kilometers of the smelters is now strongly acidic (pH < 3.5). The tufted hair grass, Dechampsia cespitosa, is now rapidly colonizing acid-metal-contaminated sites (Cox and Hutchinson 1979), which suggests that D. cespitosa may have potential for colonizing tailings. Hordeum jubatum, foxtail barley, was also used because it is a drought-resistant species that can often be found growing vigorously on disturbed sites which are on basic soils in the Yukon and N.W.T.

The commercial species assessed for their potential for re-vegetation were selected for their potential cold hardiness and some for their potential drought tolerance. All are used as part of recommended hay and pasture mixtures in Alberta and British Columbia.

## 4. MATERIALS AND METHODS

### 4.1 Collection and Preparation of Tailings

Tailings were collected from 5 sites in the Yukon, 2 sites in the Northwest Territories and one site in Ontario. The location of these sites are given in Table 1. All tailing samples were removed from the surface of old, weathered areas. Fresh tailings were also collected at two of the locations, United Keno and Cyprus Anvil, in order to compare their relative toxicities with the older, weathered tailings. The ten samples from eight tailings locations represent a wide range of pH, with different combinations and concentrations of elements. All tailings were homogenized by passing them through a 2mm sieve. Sub-samples were oven-dried at 60°C for 48 hours and analysed for both physical and chemical properties.

### 4.2 Analyses

#### 4.2.1 pH and Conductivity

Soil pH was measured in a slurry with a ratio of 5:1 water to soil. Conductivity was measured in mmhos, using a platenized conductivity bridge and radiometer.

#### 4.2.2 Elemental Analyses

Analyses for the following essential elements and heavy metals known to be present in tailings and toxic at elevated levels, were carried out using neutron activation analysis on the Slow Poke II nuclear reactor: Al, As, Ba, Br, Ca, Cl, Co, Cu, I, K, Mg, Mn, Na, U, V, W, Zn. Additional elements, Cd, Fe, Ni and Pb, were determined by atomic absorption analysis. Nitrogen concentrations of the tailings were determined using the Kjeldahl procedure (Bremmer, 1960). Total phosphorus was determined by the method described by Watanabe and Olsen (1962) for the colorimetric determination of phosphate in water extracts of soil. These were done with a Technicon auto analyzer and colorimeter. Total sulphur was determined using the LECO induction furnace and 532 titrator. Only a single soil sample for each tailing and a single soil sample from the Smoking Hills was analysed for sulphur due to limited access to analysing facilities. Soluble sulphate concentrations were determined by the method of Bardsley and Lancaster (1960), using a water-extract of the tailings.

#### 4.2.3 Physical Properties

The percent loss on ignition of tailings or soils was determined using a temperature of 450°C as recommended by Allen et al. (1974). Particle size of each of the tailings was assessed according to the following six fractions: 1 mm, 500 um - 1 mm, 250 um - 500 um, 125 um - 250 um, 45 um - 125 um and 45 um. Particles with diameters of less than 50 um were defined as silt and clay fractions (Bridges, 1970). The relative moisture holding capacity of the tailings and soils was determined (Kuja 1980). The water potential was also determined, as this is a better indicator of the 'availability' of water in tailings to plants than is moisture holding capacity. Water potential is the energy per unit volume required to remove pure water from solutions or any

material such as soil which contains water. Water potentials were measured with a psychrometric bulb after one, four and seven days in pots in a growth chamber that was set on a 16-hour light : 8-hour dark cycle at 20°C.

Lime was used on tailings in glasshouse experiments and field trials to ameliorate the low pH of acidic tailings; i.e., Arctic Gold and Silver, Cyprus Anvil and Nickel Rim. The application rate of agricultural limestone (crushed to 100% mesh, or less than 150 um) required to maintain a pH above 5.0 for tailings from Arctic Gold and Silver and Cyprus Anvil was determined in the laboratory, using a range of ratios of limestone to tailings. The pH was measured over a three-day period. Results from this experiment indicated that a pH > 5.0 could be maintained with addition of crushed agricultural limestone at rates of 1 g per 100 g and 0.5 g per 100 g (dry weight) for oxidized tailings from Arctic Gold and Silver and Cyprus Anvil, respectively.

Soil samples were taken from all limestone amended plots at the end of the experiments and the pH of these was determined.

### 4.3 Collection of Native Plant Material

The following four species were collected as rooted plants from the Smoking Hills area of Cape Bathurst, N.W.T.: the grasses Arctagrostis latifolia and Hierochloe alpina, the sedge Carex bigelowii and Artemisia tilesii, a composite. Seed of the grass Deschampsia cespitosa was collected from the Sudbury area in Ontario, and seed of foxtail barley, Hordeum jubatum, was collected from roadsides in the Yukon where it readily invades disturbed sites.

### 4.4 Glasshouse Experiments: Native Species Only

#### 4.4.1 Screening Experiment I

The relative performance of the Smoking Hills plants and seedlings of Deschampsia cespitosa and Hordeum jubatum on the various tailings was assessed under glasshouse conditions using a random block design (5 blocks x 12 treatments x 6 species). Tillers of Arctagrostis latifolia, Artemisia tilesii, Carex bigelowii and Hierochloe alpina and seedlings of D. cespitosa and H. jubatum were grown in 8 cm pots containing unamended tailings, one plant per pot. The tailings used were from Arctic Gold and Silver, Cyprus Anvil, United Keno, Venus, Whitehorse Copper, Canada Tungsten, Pine Point and Nickel Rim. For Cyprus Anvil and United Keno, both old and fresh tailings were used. Controls consisted of a garden soil and the propagation mixture.

The experiment was carried out in the glasshouse. In addition to natural light, supplementary light was given by fluorescent Gro-lights set on an 18 hr light : 6 hr dark cycle. Thirty days after planting, the plants were removed and the roots washed. Fresh and dry weights of both shoot and root tissue were recorded for each plant.

#### 4.4.2 Screening experiment II

A second screening experiment was carried out to determine if growth on the tailings could be enhanced by amendments. The four tailings used were those

on which field trials had been carried out in the Yukon, i.e., Arctic Gold and Silver, Cyprus Anvil, Venus and Whitehorse Copper. Viable seeds of Deschampsia cespitosa and Hordeum jubatum were used in the experiment because the application of seeds is the most practical approach to re-vegetating tailings sites. Since viable seed was not available from the Smoking Hills, young tillers of Arctagrostis latifolia were included in the experiment. These were raised as previously described.

A random block design was used consisting of 8 cm pots arranged in four blocks. Amendments included a) additions of crushed limestone, and b) fertilizer applications. Limestone was added to the acid tailings from Arctic Gold and Silver, and Cyprus Anvil at rates pre-determined to raise pH to 5.0. For those tailings of pH > 5.0, no such additions were made (e.g., Venus and Whitehorse Copper).

Commercial fertilizers were applied at either 0.16 g per 8 cm pot (340 kg ha $^{-1}$) or 0.80 g per 8 cm pot (1700 kg ha $^{-1}$). The fertilizers used were 1) sulphur-coated urea (32-0-0), 2) an inorganic fertilizer mixture of ammonia nitrate, superphosphates and potassium chloride (10-20-10), 3) and an organic fertilizer of activated sewage sludge (6-8-6). The numbers in brackets indicate the relative amounts of total N, available $P_2O_5$ and water soluble $K_2O$ as percentages contained in the fertilizer.

Since two different types of tailings were used (acidic and non-acidic) each with its own treatments, the experiment was divided into two sections consisting of the acid tailings (Arctic Gold and Silver, Cyprus Anvil) and the alkaline tailings (Venus, Whitehorse Copper). For the acid tailings, the experiment consisted of 4 blocks x 2 species (Arctagrostis latifolia and Deschampsia cespitosa x 2 tailings (Arctic Gold and Silver and Cyprus Anvil x 14 treatments). The treatments included two controls (a garden soil and the propagation mixture), the addition or absence of crushed limestone, the addition or absence of each of the three fertilizers (at two application rates) and factorial combinations of limestone and fertilizers.

For the non-acid tailings, the experiment consisted of 4 blocks x 3 species (Arctagrostis latifolia, Deschampsia cespitosa, Hordeum jubatum) x 2 tailings (Venus, Whitehorse Copper) x 8 treatments. The treatments included a garden and propagation mixture as controls and applications of each of the three fertilizers at two rates.

The experiment was run the in glasshouse with supplementary fluorescent lighting. The plants were grown for ten weeks and were then harvested. Fresh and dry weight determinations were then made as in the previous screening experiment.

### 4.4.3 Screening Experiment III

The screening experiment was repeated for the Cyprus Anvil tailings, only to determine the effect of raising the pH above 7.0. The application of crushed limestone was increased to 10 g per 8 cm pot. Deschampsia cespitosa seedlings and Arctagrostis latifolia tillers were used. Treatments consisted of limestone alone, or in combination with fertilizers applied at the rates of 0.16 g or 0.80 g per pot. A control mixture was also used. After 20 days all survivors were harvested and final weights were determined.

## 4.5 Field Experiments on Native Species from Stressed Environments

### 4.5.1 Unamended Tailings

Field trials were carried out using clonal material of Arctagrostis latifolia, Artemisia tilesii, Carex bigelowii and Hierochloe alpina. Plots were established at Nickel Rim (Sudbury) and at Arctic Gold and Silver, Cyprus Anvil, Venus and Whitehorse Copper. No amendments were made to the tailings. Both stratified and unstratified seed of Deschampsia cespitosa and Agrostis stolonifera collected from the Sudbury area and unstratified Hordeum jubatum seed were sown in plots (1 $m^2$) at the four Yukon sites.

Plants of a number of native species growing near the sites were also transplanted to the tailings. The following species were used: Epilobium angustifolium, Hordeum jubatum, Lupinus arcticus, Agropyron trachycaulum, Calmagrostis canadensis, Populus tremuloides, Betula glandulosa, Salix spp., Equisetum arvense and E. scirpodes, Alnus crispa, Rosa acicularis, Empetrum nigrum and Ledum palustre ssp. groenlandicum. The performance of each transplant was monitored throughout the summers of 1977 to 1980.

### 4.5.2 Amended Tailings

Field trials were made at the four Yukon sites and Nickel Rim but with additions of crushed limestone to raise the pH, peat moss to increase the moisture holding capacity of the tailings as well as to try to bind some of the toxic metals, and fertilizer to relieve the nutrient deficiency of the tailings were carried out. The amendment combinations for the different sites are shown in Tables 2 and 3.

Survivorship and growth were monitored monthly in June, July and August during 1977 and 1978. Vigour, shoot height, production of tillers and flowering culms were recorded for the transplanted material. Percentage germination, shoot and root length and shoot biomass (g dry weight) were recorded for seedlings. (The details for results of the biomass measurements can be found in Kuja (1980).)

Relative vigour was assessed for the Smoking Hills species since destructive harvests as well as long term monitoring could not be conducted at the same time. Vigour was assessed on an arbitrary scale (1-5) which was based on percentage of living shoots. Presence and degree of chlorosis (lack of chlorophyll which is often a symptom of metal toxicity), anthocyanin pigmentation, shoot growth and production of new tillers and flowers were also considered.

## 4.6 Field Experiments with Commercial Varieties

Field plots of 0.5 $m^2$ were sown with commercial seed at a rate of 1 g per plot in July 1977, 3 g per plot in August 1977 and 5 g per plot in July 1978. The species used at both Cyprus Anvil (pH 2.3-2.9) and Arctic Gold and Silver (pH 1.8-2.1) were: Bromus inermis, Lolium perenne, Alopecurus pratensis, Fesctuca arundinaceaa, Agropyron tricophorum, Coronilla varia, Deschampsia cespitosa and Hordeum jubatum. At the Venus mine site (pH 7.0 - 7.1) the following species were used: Bromus inermis, Lolium perenne, Alopecurus pratensis, Agrostis alba, Coronilla varia, Deschampsia cespitosa, Hordeum jubatum and Phleum pratense. Those used at the Whitehorse Copper site (pH 8.9 - 9.1) were

the same as at Cyprus Anvil and Arctic Gold and Silver except that Agropyron elongatum was used instead of A. tricophorum. Selections were based on the degree of waterlogging or drought potential of the sites.

Amendments of crushed limestone, peat moss, and fertilizer were used as for the field trials of native species. One of each pair of replicate plots was mulched with coarse sawdust.

Two plots, each of 0.5 $m^2$ were prepared for each amendment. In 1978, two sets of replicate plots were established at the Venus site. One was in the dry zone and the other was adjacent to a pond at the north end of the tailing site. Two sets of replicate plots were also established at Whitehorse Copper and at Arctic Gold and Silver, while at Cyprus Anvil one set of replicate plots was set up.

At the end of August 1978, all plots were sampled to determine species performance in terms of shoot biomass (dry weight). A 25 cm square wire grid was placed in each plot at the area of densest growth and all seedlings within the grid were cut off at the ground level. Seedling numbers were also counted before this harvest and subsequently in 1979 and 1980.

## 5. RESULTS

### 5.1 Chemistry of Tailings

Analyses of chemical and physical characteristics of the tailings showed each to have unique characteristics as well as common properties. Common to all were elevated concentrations of toxic elements, high sulphur concentrations, deficiencies in N and P, lack of organic matter and a coarse texture. The results of the chemical and physical analyses of the five tailings selected for the glasshouse and field trials are given in Tables 4 and 5. The detailed results from United Keno, Pine Point and Canada Tungsten can be found in Kuja (1980).

The pHs of the tailings range from 1.9 to 9.1. The tailings with pH less than 3.5 (i.e., Arctic Gold and Silver, Cyprus Anvil and Nickel Rim) clearly present a serious obstacle for re-vegetation, both because of their strong acidity and because of the increased availability of metals at low pH (e.g., Al, Mn, Pb, Cu, Ni, and Zn).

The high conductivity measurements, especially in tailings from Cyprus Anvil, indicate that soluble ion concentrations are elevated and suggest that high ionic potentials may be obtained, causing physiological drought. Sulphate levels are often a major contributor to high conductivities and perhaps significantly, the two sites with highest $SO_4^{2-}$, were also those with highest conductivity. The amount of loss on ignition (organic matter + carbonates) was very small for each of the tailings. The relatively high loss in the old, oxidized tailings from Cyprus Anvil (2.4%) compared with fresh tailings from that site (0.13%) probably resulted from combustion of sulphates and carbonates. Certainly organic matter is very low in all of the tailings. Average soils contain 15 - 30 % organic material.

All of the five tailings used in glasshouse experiments and field trials were 'sandy' in texture (Table 4).

Macronutrient concentrations for each of the tailings are shown in Table 4. Comparisons were made with concentration ranges for normal mineral soils reported by Bowen (1966) and Buckman and Brady (1970). The analyses indicate that supplies of N, P, and K are very limited in most of the tailings sampled. Very little Ca was present in the acid tailings from Arctic Gold and Silver, Cyprus Anvil and United Keno. Potentially harmful Ca:Mg ratios for plant growth exist in these tailings.

Total S concentrations were elevated in all of the tailings. The Cyprus Anvil tailings (consisting mainly of iron pyrites) present an enormous acid-generating potential, with extremely elevated S levels of 33 to 44%. The presence of soluble sulphates suggests that sulphides of the ore bodies are being oxidized in all of the tailings. Significantly, the old, weathered tailings had sulphate levels of 24,000 ppm while the fresh ones had values of 5200 ppm. The reverse order for total S levels strongly suggests oxidation of S to $SO_4$ with accompanying acid generation (pH 2.3 - 3.0 compared with 3.0 - 4.0). Much of this oxidation may be due to sulphur-oxidizing bacteria of the Thiobaccilus group.

Concentrations of several potentially phytotoxic elements are given in Table

5. Many of the tailings contained elevated levels of two or more toxic elements. Almost all of the elements would have an increased availability for plant uptake in the acidic tailings. Iron concentrations were very high in most sites and at low pH could be a significant toxic factor. The total concentrations of several toxic elements (Fe, Zn, Cd, Cu and As) were extremely elevated in tailings of higher pH and, as a result, soluble portions may well reach toxic levels even in these tailings; e.g., United Keno (old and fresh), Venus, Canada Tungsten, Pine Point and Whitehorse Copper. Greater than 5% As occurred in Venus tailings, together with 14 ppm Cd, 330 ppm Cu, 2300 ppm Pb and 18,300 pm Zn. Each tailings site has specific problems of chemical imbalance and toxicity. Overall, severe problems with Zn, Cu, As, Fe, Al, and Pb could be expected at specific sites while Ba, W, Cd, and Mn may be additional toxic factors. These toxicities may be accentuated by the deficiencies of the tailings in major plant nutrients.

## 5.2 Glasshouse Experiments: Native Species Only

### 5.2.1 Screening Experiment I. Growth on Unamended Tailings

The growth response of Artemisia tilesii, Arctagrostis latifolia, Deschampsia cespitosa and Hordeum jubatum on unamended tailings is shown in Figure 1. Variance in growth between species (including Carex bigelowii and Hierochloe alpina, not shown in the figure) and between tailings was significant at $p < 0.001$.

Artemisia tilesii was the only species that survived on all the tailings (pH range 1.8 to 9.2), with the best growth occurring on Canada Tungsten tailings. Growth on Venus, Pine Point and Nickel Rim was satisfactory although significantly less than in the controls. Growth was poor on the alkaline Whitehorse tailings and on the acidic tailings from Arctic Gold and Silver, Cyprus Anvil and United Keno. Plants became chlorotic or showed anthocyanin pigmentation on the acidic tailings from both Arctic Gold and Silver and from Cyprus Anvil, probably indicating extreme metal toxicity.

Tillers of Arctagrostis latifolia did not survive on the very acidic tailings from Arctic Gold and Silver or Cyprus Anvil. Growth was very limited on the fresh tailings from United Keno. However, on tailings from Nickel Rim and Venus growth was not significantly different from that on the control soils. The best performance by A. latifolia occurred on Nickel Rim tailings and declined through the series Venus, Canada Tungsten, Pine Point and Whitehorse Copper.

Seedlings of Deschampsia cespitosa were able to survive on Nickel Rim tailings, despite slow growth. They grew well on the old tailings from United Keno but did not survive on the other acidic tailings. Although growth on the seedling mixture was significantly better than on the tailings, growth on some of the tailings (United Keno, Venus, Canada Tungsten, and Pine Point) was not significantly different to that on garden soil. Tailings from the pH neutral sites of Venus and Canada Tungsten provided the best response for D. cespitosa seedlings.

Seedlings of Hordeum jubatum grew vigorously on all non-acid tailings, but failed to survive on any tailings with pH < 7.0. Growth on Venus, Canada Tungsten, Pine Point and Whitehorse Copper was significantly poorer than on

control soils but was significantly better than on acidic tailings. The good growth of most of the species on the near-neutral tailings, and especially on tailings from Venus, is of great interest in view of the potentially toxic chemical composition of the sites. If the purpose is purely to establish a vegetation layer on such tailings, then Hordeum jubatum seems a very effective species.

Neither Carex bigelowii nor Hierochloe alpina (not shown) grew vigorously on any of the tailings. They even grew poorly on the control soils. Neither tillers of C. bigelowii nor H. alpina survived on the acid tailings from Arctic Gold and Silver, Cyprus Anvil or in fresh tailings from United Keno, and both grew very poorly on alkaline tailings. For both species, good growth only occurred on Canada Tungsten tailings. Despite their good performance at the Smoking Hills, they do not appear useful for tailings work.

Pearson correlation coefficients were used to determine the significance of various relationships which involved growth, tailing pH, concentrations of potentially phytotoxic elements (Pb, Zn, Cd, Cu, Ni, and As) in the tailings, roots, and shoots of harvested plants from the first screening experiment.

In considering correlations between the elements in the tailings, it was found that Pb and Cd were the most highly correlated pair of elements ($r = 0.87$; $p < 0.001$). Zinc was also highly correlated with both Pb and Cd, as well as with Ni. Arsenic was positively correlated with Pb and Cd. Copper was negatively correlated with each of the other elements.

Concentrations of the metals Cu, Pb, Zn and Ni in roots were significantly negatively correlated with tailing pH; i.e., higher concentrations occurred in roots of plants growing on tailings with low pH. This suggests that uptake is pH dependent. Arsenic and Cd behaved differently in that they were positively correlated with tailing pH. The higher the pH, the greater the quantity present in the roots. Arsenic is probably present as an anion rather than as a cation in the tailings. The form of As is important in that the trivalent form $As^{-3}$ is much more toxic than the $As^{-5}$ form.

In both roots and shoots, when all species were considered together, the accumulation of each element was positively correlated with corresponding concentrations of the given element in the tailing. The elemental concentration in roots were more closely related to tailing composition than were shoot concentrations. Nickel was an exception, in that accumulation of Ni in shoots was more significantly correlated with tailing levels than were root concentrations.

For each metal, concentrations accumulated in shoots were positively correlated to levels of the given metal in the roots, i.e., shoot concentrations reflect root uptake which relates to the quantities in the tailings to which the roots are exposed. The correlation coefficients were not significant for As in Arctagrostis latifolia, Carex bigelowii or Deschampsia cespitosa. Copper and Cd gave the closest correlation between shoot and root concentrations.

Growth of all individuals correlated significantly with tailing pH. Therefore, at a low pH the growth was limited. The correlation coefficients of growth and Pb, Zn, Cd, Cu, Ni and As were also calculated. Accumulations of the elements in roots and shoots gave a better indication of how growth was being affected by these elements.

Copper and Zn concentrations in tailings yielded the most common significant negative relation with growth, i.e., high levels in tailings reflected (caused) poor growth. Species differed in their response to tailings elements. Nickel played no major role while Pb and Cd were closely co-correlated in their relation to growth.

5.2.2 Screening Experiment II. Growth on Amended Tailings

The growth response of tillers of Arctagrostis latifolia and seedlings of Hordeum jubatum to various amendments to Arctic Gold and Silver, Venus and Whitehorse Copper tailings is shown in Figure 2.

Arctagrostis latifolia grew significantly better on the control mix than on any of the lime and fertilizer amendments to the acidic tailings of Cyprus Anvil and Arctic Gold and Silver. None of the tillers survived on Cyprus Anvil tailings regardless of the amendments made to the tailings (not shown in the Figure). These tailings are remarkably toxic. Growth occurred on Arctic Gold and Silver tailings in which acidity was reduced with limestone additions (pH > 5.0) (Figure 2). Fertilizer applications at low rates equivalent to 34 g $m^{-2}$ improved performance when limestone was present; in the absence of limestone, the tillers did not survive, regardless of which fertilizer was applied. The best fertilizer response was to the low rate of sulphur-coated urea (32-0-0) in the presence of limestone. Growth on these amendments was not significantly different from growth on garden soil. High rates of inorganic fertilizer applications killed the tillers. Yet, such application rates would be appropriate for agricultural species.

A. latifolia grew on all of the amended non-acid Venus tailings (Figure 2). However, on the high nitrogen and high phosphate treatments growth was poor (i.e., sulphur-coated urea (32-0-0) or inorganic fertilizer (10-20-10) applied at 170 g $m^{-2}$). Best growth occurred on Venus tailings amended with the high phosphate treatment (10-20-10) applied at the lower rate (34 g $m^{-2}$). In contrast, A. latifolia grew poorly in all treatments on the non-acid Whitehorse Copper tailings, whether amended or unamended (not in Figure).

Hordeum jubatum seedlings responded to several fertilizer amendments on Venus and Whitehorse Copper tailings (Figure 2). Growth on Venus tailings amended with high rates of organic (6-8-6) or inorganic fertilizer, high in phosphates (10-20-10), was best but significantly less than on the garden soil and seedling mix control. However, these seedlings performed poorly on amended tailings from Whitehorse Copper, where the best growth occurred on tailings with either low or high application rates of inorganic fertilizer (10-20-10).

Although seedlings of Deschampsia cespitosa grew on some of the basic unamended tailings, growth on the amended tailings was very poor. No seedlings survived on the tailings from Cyprus Anvil and few survived on tailings of Venus and Whitehorse Copper, regardless of the amendments. Some seedlings survived on Arctic Gold and Silver tailings to which crushed limestone had been added to increase the pH to greater than 5.0 and to which fertilizers, inorganic (10-20-10) or organic (6-8-6) had been applied at high or low rates. However, growth of these seedlings was not as good as that of Arctagrostis latifolia.

### 5.2.3 Screening Experiment III

In this experiment, Cyprus Anvil tailings were limed to a pH $\geq$ 7.0. None of the tillers of Arctagrostis latifolia or seedlings of Deschampsia cespitosa survived. Viable seeds of D. cespitosa sown with the seedlings failed to germinate. The fertilizer additions had no effect in this experiment. These tailings are remarkably toxic, due to multiple metal tolerances and a very high acid generating potential.

## 5.3 Field Experiments on Native Species from Stressed Environments

### 5.3.1 Unamended Tailings

None of the four species transplanted to unamended tailings of Cyprus Anvil or Arctic Gold and Silver survived. Seeds of Agrostis stolonifera and Deschampsia cespitosa from Sudbury, and Hordeum jubatum also failed to germinate on these unamended tailings plots.

At the Nickel Rim site, all clones of the Smoking Hills species survived over the first three years of the trials, though only Arctagrostis latifolia continued to spread and flower up to 1981 (Figure 3). It was still surviving and spreading in 1985 and D. cespitosa is also seeding and spreading at the Nickel Rim site.

Only two of the transplanted species, Arctagrostis latifolia and Artemisia tilesii, survived on the unamended Whitehorse Copper tailings into 1979 but only the Arctagrostis was flowering and growing vigorously (Figure 4). Hordeum jubatum was the only local species that grew vigorously on the unamended tailings. All transplanted Hordeum clones matured and seeded in the summer of 1977, and again in 1978 and 1979. As in the Venus tailings, some seeds of Deschampsia cespitosa, Agrostis stolonifera and H. jubatum germinated, but none of the seedlings survived.

The performance of Arctagrostis latifolia on the unamended Venus tailings (Figure 4) was not as good as that on the Whitehorse Copper tailings. The clones survived from 1977 to 1980 but did not grow well, partly due to grazing by ground squirrels and to submergence under wind-shifted tailings.

Local species grew most vigorously on the Venus tailings. Some shrub species, Salix planifolia, Salix spp., Populus tremuloides and Betula glandulosa, were still growing three years after the transplant. The grasses Calamagrostis canadensis and Agropyron trachycaulum and the fireweed Epilobium angustifolium survived on the unamended tailings but did not flower. The clumps of Hordeum jubatum which were obtained near the site and transplanted to the tailings flowered and produced fruit. By 1980, they had spread and new seedlings were evident.

### 5.3.2 Amended Tailings

A) Cyprus Anvil Tailings

i) The Smoking Hills species responded poorly in the summer of 1977 to amendments to the Cyprus Anvil tailings. The plants which did survive were

chlorotic and no new shoot growth was observed. It was not possible to determining long-term survivorship since the site was flooded with fresh tailings in the spring of 1978.

ii) Seeds of Deschampsia cespitosa and Hordeum jubatum failed to germinate in plots set out in 1977 and 1978, regardless of the amendments to the tailings.

iii) Similarly, none of the native species transplanted from areas around the tailings site survived on the 1977 or 1978 plots regardless of the amendments.

B) Arctic Gold and Silver Tailings

i) At the end of the first summer, the response of all the Smoking Hills clones was much better on tailings amended with limestone. Arctagrostis latifolia again performed best, followed by Artemisia tilesii, with the greatest response on the limestone-alone amendment. However, survivorship was poor by the end of the following summer and the plants were very chlorotic and necrotic. Despite this, plants were still surviving in the 4th growing season, 1980. In the lime-only plots, 9 of the original 12 plants still survived and 4 of these were flowering. In the lime+peat plots, 3 clones were alive and one was flowering. In the peat+6-8-6 treatment only one clone was alive. Interestingly, the lime-only plots had a pH of 6.8, while the lime+peat had fallen to 2.0. Peat generates its own acidity.

ii) There were only a few survivors from the seedlings of Deschampsia cespitosa and Hordeum jubatum planted in July 1977. However, a second seeding in the autumn of 1977 produced seedlings which survived through the summer of 1978, but only on the limed plots. All of these seedlings had died by the summer of 1980.

A re-seeding of the original plots in June 1978 showed that seeds failed to germinate in the tailings which were not limed. Deschampsia cespitosa seedlings gave the best response to amendments of limestone plus inorganic fertilizer (L+21-7-14, L+10-20-10) or limestone plus organic fertilizer (L+6-8-6) at low application rates (34 g $m^{-2}$). Peat additions had a negative effect on the number of survivors of both species. By August 1980, survivors of D. cespitosa still occurred in four of the limed plots: L+P, L+10-20-10, L+P+6-8-6 and L+P+21-7-14, though all seedlings were small. Survival of H. jubatum seedlings was not improved by additions of organic fertilizer to limestone amendments.

iii) None of the local species transplanted in 1977 to the amended tailings plots survived. Two grasses, Calamagrostis canadensis and C. purpurescens were still alive in July 1979, on amendments of limestone plus peat and inorganic fertilizers (L+P+21-7-14, L+P+10-20-10) that were started in June 1978. Clonal material of Arctagrostis latifolia, which was collected from acidic shales in the Eagle River area of the Dempster Highway in the Yukon in early August 1978, and transplanted to the amended plots as local species, appeared to be very healthy at the end of August 1978. In August 1980 it was noted that the Dempster Hwy. material was doing very well; it was spreading and flowering. Its best performance was on the L+P+10-20-10 amendment.

C) Venus Tailings

i) On the Venus tailings, the Smoking Hills species did not respond as well

as anticipated based on the results of the glasshouse experiments. Arctagrostis latifolia responded better than the other three species, with the greatest vigor on the peat amendments. In July 1980, in the wet area of the site, 2 clones were flowering in a peat-only treatment and on the peat + 6-8-6 fertilizer plots growth was excellent, with three plants flowering. On the dry site, the plants survived but growth was poor.

ii) The survival and growth of Deschampsia cespitosa seedlings was markedly better on the wet site than on the dry site (Figure 5). At the wet site, D. cespitosa seedlings grew well on unamended tailings and on fertilizer amendments without peat. The best response was to the organic fertilizer. A greater number of seedlings survived on amendments of organic fertilizer or sulphur-coated urea at low application rates (34 g $m^{-2}$) than at high application rates (170 g $m^{-2}$). Poorest growth and performance was in the unamended plots and also in the 32-0-0 amendment and the P+32-0-0 amendment, and in peat only plots. Best growth with vigorous flowering was in the peat + 21-7-14 fertilizer. Flowering also occurred in the P+10-20-10 and in the 21-7-14 and 10-20-10 treatments without peat additions. Growth in the dry site, in contrast, was poor or non-existent.

The greatest number of survivors of Hordeum jubatum occurred on the plot with the inorganic fertilizer (10-20-10) amendment which had been mulched with sawdust (Figure 5). The results for amendments made to the tailings in June 1978 were much better on the wet site near the pond than on the dry site. Peat additions increased the number of survivors in all fertilizer treatments and on unamended tailings.

iii) Hordeum jubatum transplants grew vigorously on the Venus tailings on both amended and unamended plots. The plants flowered, matured and set seed in the summers of 1977-1980. By 1980, in the dry sites, new seedlings had been produced and were spreading. The species seemed very drought-tolerant.

The grasses Calamagrostis canadensis, C. purpurescens and Agropyron trachycaulum survived on all amendments with the best response on peat + organic fertilizer or peat + sulphur-coated urea in the wet site. Clonal material of Arctagrostis latifolia, collected from the Eagle River plain on the Dempster Highway was transplanted to the various amended plots in mid-August, 1978, and was not showing any signs of stress when final observations were made in 1980. These plants were surviving in July 1980 and flowering in the P+6-8-6 amendments. Some of the other native species transplanted survived the first summer, but most were dead by the following year.

D) Whitehorse Copper Tailings

i) Approximately two weeks after amendments had been made and clonal material was transplanted to the various plots, a number of the plots were accidentally covered by fresh tailings which contained considerable moisture to a depth of several inches. Many of the clones that had been submerged by these fresh tailings had grown up through them by the end of August 1977. The growth of Arctagrostis latifolia and Artemisia tilesii was considerably greater than for Carex bigelowii and Hierochloe alpina (Figure 4).

The best growth for both A. latifolia and A. tilesii occurred either on unamended tailings or in response to amendments of peat plus inorganic fertilizer (P+10-20-10) (Figure 4) on which A. latifolia flowered. It should be

noted that the plots amended with this treatment (P+10-20-10) had not been flooded by fresh tailings.

ii) Deschampsia cespitosa failed to germinate on any amended plots, when sown in July 1977 or June 1978. As a result of re-seeding in Sept. 1977, there was a high survivor rate on a number of plots the following summer (Figure 6). Seedlings from spring sowing seemed to suffer from summer drought. Unfortunately, some plots were destroyed by the fresh tailings which were pumped onto the site throughout June 1978.

A number of seedlings survived on each of the remaining plots. With the exception of the peat plus organic fertilizer (P+6-8-6) amendments, the remaining mulched plots had better response than had occurred on unmulched plots. The best response was to peat additions with the 10-20-10 fertilizer (mulched) and to peat plus the organic fertilizer (unmulched).

Seeds of Hordeum jubatum germinated in the summer of 1977. Survivorship was better on mulched plots; the best germination occurred on amendments of organic fertilizer and mulch (Figure 6). The plots were re-seeded in Sept. 1977. All the unmulched plots as well as mulched plots amended with peat plus organic fertilizer and peat plus sulphur-coated urea, were destroyed in the spring of 1978. Peat additions had a positive effect when included in amendments.

In plots which were not amended with peat, Hordeum jubatum responded best to organic fertilizer. In plots which received peat additions, peat plus inorganic fertilizer (P+10-20-10) had the highest number of surviving seedlings. The best performance recorded in 1979 in the plots set up in July 1978 was in the P+10-20-10 (109 survivors), the 10-20-10 (123 survivors) and in the 6-8-6 (106 survivors).

iii) Of the local species, Hordeum jubatum showed the best response and survived on all plots. In both 1978 and 1979, the plants grew vigorously, flowered and produced viable seed. The other local species, such as Agropyron trachycaulum and Calamagrostis canadensis, when they survived, were desiccated.

E) Nickel Rim Tailings

The performance of Deschampsia cespitosa after one growing season (May-Sept. 1978) is presented in Figure 3. Where limestone was applied to raise the pH to greater than 5.0, a substantial number of seedlings survived. There were no survivors on plots that were not limed. The percentage of seedlings that survived was significantly higher for amendments of crushed limestone and inorganic fertilizers (L+21-7-14, L+10-20-10) than for amendments of limestone and organic fertilizer (L+6-8-6) or limestone and sulphur-coated urea (L+32-0-0). By 1981, plants were well established on the limed plots, especially at their periphery. Flowering and the best vegetative growth occurred in the L+6-8-6 treatment.

5.3.3 Accumulation of Metals in Clonal Material and Seedlings

Concentrations of Pb, Zn, Cd, Cu, Ni and As were determined for a number of shoots from clones and seedlings surviving in the various amendments at Arctic

Gold and Silver, Venus and Whitehorse Copper sites at the end of August 1977. Shoots were removed from the Smoking Hills species growing on the unamended tailings at Nickel Rim in Sept. 1977, one year after the clones were transplanted to the tailings sites. Results are shown in Table 7.

A) Nickel Rim Tailings: Shoots of Arctagrostis latifolia, which had grown vigorously on the unamended tailings, accumulated Ni, Cu, and Zn to a limited extent, while shoots of Carex bigelowii, which were chlorotic and necrotic, accumulated substantially higher levels of these metals. Lead and Cd concentrations were also higher in shoots of C. bigelowii than for A. latifolia.

B) Arctic Gold and Silver Tailings: At this acidic site, green shoots removed from Arctagrostis tilesii that had survived on limed plots had accumulated Pb, Zn (153-193 ppm), Cd, Cu, Ni and As to some extent. However, necrotic shoots removed from dead plants of Hordeum jubatum from unamended tailings had very high levels of Cu, Zn and especially As (2320 ppm). One could suppose that this accumulation of As and of Zn may have been a factor in the death of the plants, but it is also possible that the dead shoots acted a wick for evaporation of water, concentrating the metals which were then left behind.

C) Venus Tailings: All the vegetation from Venus accumulated high concentrations of Zn compared with Pb, Cd, Cu, Ni and As. Shoots of Equisetum scirpoides and seedlings of Deschampsia cespitosa on unamended tailings accumulated much higher concentrations of each metal, especially As, while D. cespitosa was also a foliar accumulator of Pb and Zn. Their shoots were purple from anthocyanin pigments and were moderately dessicated but all were alive. Green leaves harvested from one Salix planifolia shrub transplanted to the tailings in June, accumulated elevated levels of zinc (180 ppm). Metals were accumulating in the shoots of survivors and Zn concentrations were especially high in the foliage of healthy green shoots.

iv) Whitehorse Copper Tailings: Shoots were removed from clonal material of each of the Smoking Hills species on all plots. Copper, which is present at very high concentrations in the Whitehorse Copper tailings, was elevated in all tissue samples, despite the high pH (9.1) of this site. Amendments did not appear to reduce or enhance elemental uptake. Copper levels in the foliage were certainly sufficiently high to suggest severe problems of copper toxicity to these plants. While unamended tailings yielded foliar Cu concentrations greater than 230 ug $g^{-1}$ dry weight for all species, the grass Hierochloe alpina accumulated 475 ug $g^{-1}$ dry wt. of Cu on these tailings.

## 5.4 Field Experiments with Commercial Species

As reported for the native species, both the tailings site involved and the species concerned exerted a profound effect on germination, survival and growth. The two acidic tailings sites were strongly adverse to plant growth. Even with massive lime additions Cyprus Anvil tailings maintained a powerful phytotoxicity. At other sites some of the commercial varieties shared good surroundings, depending upon the lime and fertilizer treatments used. A brief description of these responses follow:

A) Arctic Gold and Silver Tailings

For the plots established in 1977, the liming rate was insufficient to

maintain a pH of greater than 5.0. Nevertheless, several species survived through the summer of 1977 and 1978. By 1979, nearly all were deaad. Often the seedlings developed a deep anthocyanin pigmentation on this site. The pH of the limed plots declined over time, so that in 1979, the pH of the lime and peat treatment (L+P) had fallen from 7.1 to 2.0. The L+P+32-0-0 fell from pH 6.9 to 2.5 over the same period. Lime only maintained a pH of 6.8. Such pH drops are likely to be catastrophic to roots.

The 1978 seedlings at a higher liming rate maintained pH well above 5.0. Commercial species responded well to these limed plots but there were no survivors on plots which had not been amended with crushed limestone.

On this site, no clear beneficial effect of mulching was noted. Alopecurus pratensis had the greatest density per plot of any Alopecurus species used both on mulched and unmulched plots. However, as a percentage of seeds sown, the performance of Agropyron tricophorum was markedly better. Interestingly, the two native species raised from seed, Deschampsia cespitosa and Hordeum jubatum did better in both survivorship and in density per plot than the agricultural species.

From the 1978 sowing, survivorship was much better. Agropyron tricophorum, Festuca arundinacea or Bromus inermis all had greater than 10% of survivors in 1979 from seeds sown in June 1978. Coronilla varia had no survivors on any amendment, while Lolium perenne responded well to fertilizer amendments.

Statistical tests (Duncan's Multiple Range) generally showed that fertilizer additions gave significantly greater mean densities of biomass per plot for all species. Peat additions appeared to have a slightly detrimental effect on seedling survival.

It will be also noted that additional germination occurred in 1979 so that spring germination may be an important feature of fall sowing for commercial varieties. For Festuca arundinacea on Arctic Gold and Silver tailings, the best biomass response occurred with lime + peat + 10-20-10 fertilizer, and next-best response with lime + 21-7-14 fertilizer. This coincided with survivorship in 1979. Good survivorship also occurred with L+6-8-6 and L+10-20-10. Agropyron tricophorum was surviving in a rather uniform manner in 1979 from sowing made in 1978. In terms of biomass, however, L+P+10-20-10 again proved the most successful treatment, with the plants on the high nitrogen treatment (L+P+32-0-0) also doing well. Certainly, it seems as if nitrogen may be a major limiting factor on the Arctic Gold and Silver mine site, in addition to the acidic conditions. The response of D. cespitosa and H. jubatum have been referred to previously.

B) Venus Tailings

Comparing the dry and wet sites, it is apparent that survival was much worse in the dry areas. The largest number of survivors occurred with Phleum pratense and the highest percentage survivors of seeds sown (0.3%) was for Bromus inermis in 1979. Bromus is known to be drought-tolerant, and also has a large seed size which may account for its good performance. In the wet areas, B. inermis again showed that highest percentage survival in 1979 of the species used (4.2%), Lolium perenne (3.2%), Alopecurus pratensis (1.7%) and Phleum pratense (1.0%) also were surviving quite well. The two native species grew well on this wet site, with H. jubatum showing a 16% survivorship in the

second growing season, and flowering in the third year.

On the dry site, fertilizer or peat additions had very limited success in increasing survival and a good many seedlings died in 1978. This was undoubtedly the result of drought. Phleum pratense responded best to P+21-7-14 and to 6-8-6 treatments on the dry site. The addition of peat did not notably improve performance.

On the wet site, it seems that P+32-0-0 had an inhibitory effect while 10-20-10 gave the best results. Virtually nothing survived from 1977 on either site, nor from 1978 on the dry area. In contrast, performance on the wet site was good. Best response was to the high rate of application of 6-8-6.

C) Whitehorse Copper Tailings

It will be recalled that an emergency discharge of tailings in 1978 flooded some of the plots and that this was worsened in 1979, so that the 1979 and 1980 data are largely uninformative for the flooded plots. The Whitehorse site is also drought prone. In both 1978 and 1979, the best performance in both mulched and unmulched plots was by Agropyron elongatum. Bromus inermis was the next best survivor. Mulching appeared to be a useful treatment at Whitehorse Copper.

From the 1978 sowing, two species stood out in their seedling survival. They were A. elongatum and the native grass H. jubatum (13.2 and 6.8%, respectively). The response of A. elongatum to amendments differed between the years. For the 1978 sowing, best survival was in the 10-20-10, P+10-20-10 or P+6-8-6 amendments. Again, the 32-0-0 did not survive as well as unamended or peat only treatments.

## 6. DISCUSSION

In these studies, we have attempted to assess the potential of a number of native species to establish on and colonize strongly phytotoxic mine tailings. The tailings selected differed widely in their chemical composition, in acid generating potential and in pH. The plant species tested were selected because of their known ability to grow in adverse northern environments, and under conditions of both strong soil acidity and potential heavy metal toxicity. These selections included four species from the Smoking Hills, which are amongst the most tolerant of the acidic sulphur fumes and soil toxicity occurring there (Hutchinson et al. 1978), as well as a grass from the Sudbury area which has invaded the industrial barrenlands near the metal smelters since 1972 (Cox and Hutchinson 1981). In addition, seeds of the foxtail barley, Hordeum jubatum, which invades waste ground and road edges, were collected in the Yukon and also used in experiments. This species was selected because it is found on alkaline soils and it is both salt and drought tolerant; features which were felt to be of great importance for survival on many tailings sites.

### 6.1 Potential of Smoking Hills Species for Re-vegetation of Mining Areas

Leaving specific fertilizer, lime and peat amendments aside, both the laboratory and field experiments showed quite clearly that, indeed, some native species from selected sites of occurrence, had a remarkable ability to grow on otherwise highly toxic tailings. The most striking example of this has been the performance of the Smoking Hills grass Arctagrostis latifolia at the Nickel Rim site in northern Ontario, which has a pH of 3.3. On this site, transplants made in August or September 1976 have successfully survived 9 growing seasons. They are spreading and have flowered each year since 1977. The seeds produced are viable. The species as a whole has admirable properties of vegetative spread, so that it can effectively colonize an area once seedlings are established. The field grown A. latifolia at Nickel Rim were given no lime or fertilizer amendments. Yet, attempts to colonise these tailings using commercial varieties with lime and fertilizer amendments have largely failed.

Of the other Smoking Hills transplants, the next best species on the range of tailings tested was Artemisia tilesii. In the greenhouse experiment, it was actually able to survive without amendment across the range of tailings tested, i.e., from pH 1.8 to 9.1. However, the lack of vegetative vigor, inability to spread and lack of flowering at the field sites suggest that A. tilesii will not be a useful species for tailings re-vegetation work, despite its exceptional ability to tolerate a very wide range of soil acidities.

Both the sedge Carex bigelowii and the grass Hierochloe alpina from the Smoking Hills did poorly on most of the tailings sites. Part of this was undoubtedly due to their preference for wetter sites, which the tailings did not generally provide. It is also apparent from the glasshouse experiment, that even when an adequate water supply was continually provided, these two species were not sufficiently tolerant of the toxic elements in the tailings.

Thus, it is apparent from the results that only Arctagrostis latifolia of the Smoking Hills species has real potential for re-vegetation of highly toxic

tailings of a wide range of pH. This is hardly surprising since the selected tailings sites for field work are very toxic and have almost completely excluded natural invasion by native species and have, in several cases, tremendous acid-generating potential. Perhaps the surprising thing is that we could find even one species which seemed to have a very high potential for successful colonization. For several sites, it was able to survive, spread and flower on unamended sites. On several others, it survived where minimal lime additions were made. Since the clones collected from an acidic site along the Dempster Highway showed equally fine properties to those of Smoking Hills material, it seems likely that this extreme tolerance to widely different tailings acidities and alkalinities, and to high concentrations of toxic elements in the soil solution (e.g., Zn, Pb, Cu, Ni, As, Cd) may be widespread within the species. Indeed, it may be a feature of many northern populations of A. latifolia. Its ability to colonize disturbed sites in the arctic and sub-arctic has been reported from a variety of studies (e.g., Klebesadel 1965). If this invasiveness is indeed a widespread phenomenon of this species, then one does not need to rely on the limited and inaccessible Smoking Hills plants for re-vegetation work. It is also possible to obtain seeds of several strains of A. latifolia from W. Mitchell at the University of Alaska in Palmer, Alaska.

The problem with all of the Smoking Hills species used is the difficulty in obtaining viable seed for them at the Smoking Hills. Clearly, having to dig up clonal material from the Smoking Hills is not a viable proposition since the costs would be prohibitive, and the sites are limited to a few square kilometres. Consequently, the possibility of populations of Arctagrostis latifolia being acid- and metal-tolerant in less remote sites is an exciting one. Some preliminary tests on material from Alaska suggests that this may have considerable Ni, Cu and Al tolerance, even though this is from seed developed for seeding of merely disturbed areas. Commercial quantities of A. latifolia seed would not take more than a few years to develop.

## 6.2 Potential of Native Species for Re-vegetation of Mining Areas

The two native species tested from seed, rather than from clonal material, were Dechampsia cespitosa from Sudbury and Hordeum jubatum from the Yukon. Our hopes for D. cespitosa were high because of the Sudbury population's remarkable tolerances to a number of toxic heavy metals concurrently and because of its occurrence on acidic, metal-contaminated soils in the Sudbury area (Cox and Hutchinson 1979, 1980, 1981). These hopes were not fully realized, though it has been able to establish and flower at a number of sites, and has also survived droughts and flooding at these tailings sites for up to 4 growing seasons.

In the field, its best performance was on the Nickel Rim tailings. Here, where lime was added to raise the pH above 5.0, a substantial number of seedlings survived. While lime additions were essential to allow good growth, once established, the plants grow well and have seeded successfully outside of the original plot. The plants also showed a response to fertilizer on the plots.

The main problem for D. cespitosa being used for tailings re-vegetation is that it is not particularly drought-tolerant. On very dry tailings, it simply died.

The other native species tested by seed sowings was Hordeum jubatum. The glasshouse experiment showed a very clear cut pattern for this species. It grew well on neutral and alkaline tailings, and failed miserably on all the acidic ones. This, and its natural occurrence in disturbed and drought-prone areas, led us to hope it would be a successful colonizer of Venus and Whitehorse Copper tailings.

Venus was the success site for Hordeum jubatum. Seeds germinated well and were able to survive in both the dry and the wet areas. Survivors occurred in both unamended and amended sites. Peat addition on this pH neutral site appeared to be beneficial to Hordeum.

## 6.3 Local Transplants

As might be predicted from the above, the local transplants of Hordeum jubatum grew well and flowered on the Venus and Whitehorse Copper tailings. At the time of termination of the experiments, it seemed that Hordeum would be able to spread across much of the dry area of the tailings. The grasses Calamagrostis canadensis, C. purpurescens and Agropyron trachycaulum also showed potential as local transplants onto tailings, but amendments increase their ability to survive.

The performance of other local transplants such as Epilobium angustifolium, Equisetum arvense, and E. scirpoides was generally poor, even though the latter two species were amongst the most common natural invaders of the wet tailings area at Venus. In the boxes of local soil sunk into the various tailings to determine local seed inocula, it was found that Epilobium angustifolium was the most common invader, demonstrating that it was kept off the tailings by their chemical conditions.

## 6.4 Effects of Amendments on Survival

A number of species-fertilizer effects were quite specific to the tailings sites. Nevertheless, a number of generalizations did develop, which, while somewhat obvious, are of fundamental importance.

Firstly, lime additions to the strongly acidic sites was often essential to allow transplants and seedlings to survive. Even though the intention was merely to raise the pH to > 5.0, because of the initial very low pHs (1.8, 3.2, 3.5, etc.) and the tremendous quantities of sulphur, as sulphide, with consequent high acid generating potential, sometimes massive quantities of lime was essential. Arctagrostis latifolia was able to grow well at pH 3.0 or greater, except at Cyprus Anvil which killed everything planted or sown in it. For other species, a minimal pH of 4.0 seems important for good growth.

Transplants seemed better able to cope with very low pH than do seedlings. This, however, probably relates to secondary effects: especially that of drought. One major benefit of liming is to immobilize in the tailings the soluble heavy metals and toxic elements which are otherwise available for root uptake at low pH. A third factor is that lime adds calcium to the plants and the soil, which, by itself, reduces aluminum toxicity as a result of competitive uptake. It also increases the Ca:Mg ratio, which is unfavourable for good growth at a number of the sites tested.

The application rate of crushed limestone of 9 kg $m^{-2}$ and 10 kg $m^{-2}$ at Arctic Gold and Cyprus Anvil, respectively, is very high and would be prohibitively expensive for large areas. Even this high liming rate failed to allow growth at Cyprus Anvil because of extreme metal toxicity problems. At Arctic Gold and Silver, the site is small and unless a top layer of local soil or inert material is added, an appropriate massive liming dose is essential.

Peat additions had either beneficial or harmful effects. This was often dependent upon the acidity of the site involved. On neutral or alkaline sites, peat additions had a beneficial effect (e.g., at Venus and Whitehorse Copper) but only when combined with fertilizer additions, since, although they reduced the pH somewhat as a result of acid generation, this was not sufficient to cause acidity problems on these very well buffered tailings. The benefits undoubtedly were due to the peat increasing the water-holding capacity of the drought-prone tailings, and also may well have been due to chelation and immobilization of some of the toxic elements such as As, Zn, and Cu by cation exchange and adsorption on to the organic matter.

The results of the mulch additions at seeding time in the field were somewhat equivocal. The sawdust mulch inhibited seedling survivorship in some plots, especially for Deschampsia cespitosa. The dense layer of sawdust probably reduced light and absorbed moisture from precipitation and dew, reducing the moisture from percolating to the seedlings beneath. It seems possible, however, that a straw mulch would allow better water movement after rains.

Generally, the addition of fertilizers improved performance of seedlings and transplants, provided the pH was in a range suitable for growth, which often involved lime additions. High phosphate additions were necessary on the metalliferous tailings, since P was low or unavailable as the result of formation of insoluble phosphates with Al, Zn, Pb etc. For the Smoking Hills species, adapted as they are to a region of low N and P, it might be anticipated that responses to fertilizers would be much less for these species than for the seedlings of the Deschampsia cespitosa and Hordeum jubatum and for the commercial species. Generally this was true, with the Arctagrostis latifolia especially, often showing best response to the organic 6-8-6 additions, which provide a slow release, low level of N, P and K.

The specific species-tailings responses to each fertilizer are clear, and suggest that pot trials must be carried out for each tailings site before fertilizer amendments are made to tailings, or else a valuable and costly resource will be wasted. The fertilizer problem is accentuated in the field on many tailings sites, in that if application is followed by a drought, then no nutrient release occurs and the seedlings do not have the benefit of major nutrient supplements which would enable them to root more deeply and survive the drought.

## 6.5 Performance of Commercial Species in the Field

The overall responses of the 9 commercial grasses and legumes used in the field trials in 1977 and 1978 paralleled, to a large extent, those of the native species, though there was nothing to compare with the performance of Arctagrostis latifolia on amended tailings.

It seems as if some of the commercial species have a lot of promise on some of

the tailings, given the right amendments. These include Festuca arundinacea, Alopecurus pratensis, Bromus inermis and Lolium perenne on the acidic Arctic Gold tailings, and B. inermis, L. perenne, A. pratensis and Agropyron elongatum on neutral and alkaline sites, where drought is a major factor. Under wet conditions, Phleum pratense may be the best species to use.

## 6.6 Effects of Tailings on Elemental Uptake of Vegetation

It is clear that heavy metals in elevated concentrations were taken up by the plants when grown on tailings. Each of the tailings sites imposes a particular pattern of plant uptake between elements. Liming clearly reduced elemental uptake on the acidic Arctic Gold and Silver tailings (e.g., for As, Cu and Zn). Hordeum foliage accumulated 2332 ppm As at this site, whereas with lime additions foliar levels in A. latifolia and A. tilesii were less than 20 ppm. On the other highly arsenic-contaminated site, Venus, the species differed enormously in their As content.

On Whitehorse tailings, the major accumulation was of Cu, which reached 475 ppm Cu in the foliage of Hierochloe alpina when on unamended plots.

The severe toxicity of the Cyprus Anvil tailings is probably related to zinc which enters the plants in massive quantities, reaching levels > 10,000 ppm Zn in A. tilesii and > 5008 ppm in all other species. Root concentrations were even higher. Zinc is very probably the critical killing factor. Copper was also elevated compared with 'normal' and could be an additional factor.

Clearly, metals do occur at high concentrations in the foliage and roots of plants growing on metal-contaminated tailings. In some cases the concentrations could be a serious wildlife hazard if eaten by grazers. They could also enter the food chain for higher trophic levels. However, we have observed enthusiastic colonies of ground squirrels burrowing and living in various grossly contaminated sites. They also grazed to ground level the shoots of vegetation we had planted. It would be of interest to determine the accumulation of elements in such animals, and also to determine the percentage of their diet they obtain on tailings. We believe this latter will be very small, but that ingestion of tailings would be a primary route of toxic metal entry to the animal.

Correlations between root elemental concentrations and tailings were even higher, with all of the above elements having $p < 0.0001$. For roots, As yielded the most significant values, followed by Cd and Zn. The suggestion is that As and Zn readily enter the root, as does Cd, Cu, Ni and Pb, but that Cd and Ni move more readily from the root to the shoot, while As is much less mobile in the plant. When this is examined on a species by species basis for the native species used, the hypothesis is confirmed. Correlation values for shoot:root elemental levels were > 0.9 for Cd and Ni in Hordeum jubatum, and for Cd and Zn in Deschampsia cespitosa. Indeed, only As yielded non-significant values, and this for 3 of the 6 species. Tailings pH had a substantial effect on metal availability, and for each of Cu, Pb, Zn and Ni greater uptake into shoots and root occurred at lower pHs, while for As greater uptake appeared to occur at higher pHs. Cadmium was of especial interest in that uptake appeared independent of pH.

Since it has been implicitly assumed that the presence of toxic elements in

soluble form in tailings causes reduced growth as a result of their uptake and subsequent interference with metabolism, the correlations between the elemental concentrations in the roots and shoots and the performance (growth) of these same plants is of special interest. It is apparent that Zn concentrations in the plant almost always related significantly to growth. The relationship is that of a toxic element, in that the correlation coefficients are always negative. Foliar Zn levels in D. cespitosa and A. latifolia were particularly closely related to growth. For Artemisia tilesii Cd and Pb levels in shoots and roots correlated better with growth than did Zn, so that for this species, the availability of these elements may have been critical in determining performance. Shoot concentrations of Cu in every case correlated significantly with growth. The correlation patterns strongly support the idea of differences in tolerance to metals of various plant species, and also suggest that for many of the tailings sites the toxic effects were the result of Zn and Cu availability. Arsenic had very little influence on growth, while Cd sensitivity in Artemisia tilesii may have been a decisive factor on some tailings.

## 6.7 Conclusions

Overall, it is clear that the challenge provided by the toxic tailings to the native species, and to the commercial ones used in the experiments by the tailings selected was a severe one. In view of the chemical analyses of the tailings, it is perhaps surprising that only the Cyprus Anvil tailings proved too toxic in the field for any amendment and species combination we tried. A good deal of future work will be needed to come up with a satisfactory revegetation scheme for this large tailings area. Despite the remarkably harsh chemical and physical conditions of the other sites, and our deliberate selection of the worst sites for field trials, at each site except Cyprus Anvil, we had at least some success with the native species, often without lime or fertilizer amendments, though these improved survival and growth. The grass Arctagrostis latifolia appears especially useful. Even the commercial species used showed some promise under particular conditions of amendment. The unique nature of each tailings presents a great challenge with few generalized solutions. It would be essential in attempting to re-vegetate any tailings area that a detailed chemical analyses be carried out, time requirements established, and preliminary bioassays be made in the field to determine the most useful native and commercial species. On particularly 'difficult' tailings, there are strong advantages in the use of selected native species. Agriculture Canada should be approached to provide commercial quantities of metal- and acid-tolerant seed of Arctagrostis latifolia and Deschampsia cespitosa for use on northern tailings.

## 7. REFERENCES


Allen, S.E., H.M. Grimshaw, J.A. Parkinson and C. Quarmby (eds.) (1974). Chemical Analysis of Ecological Materials. John Wiley and Sons Inc., New York, pp. 45-68

Andrews, R.D. (1977). Tailings: Environmental consequences and a review of control strategies. In: Hutchinson, T.C. (ed.) International Conf. on Heavy Metals in the Environment, Symposium Proc., Toronto, Vol. II, Part 2, pp. 645-675.

Antonovics, J., J. Lovett and A.D. Bradshaw (1967). The evolution of adaptation to nutritional factors in populations of herbage plants. In: Studies in Plant Nutrition and Physiology IAEA/FAO, Vienna, pp. 549-567.

Ayerst, J.M. (1978). The effect of compaction of coal shale on revegetation of spoil heaps. Reclamation Review 1: 27-30.

Bardsley, C.E. and J.D. Lancaster (1960). Determination of reserve sulphur and soluble sulphates in soils. Soil Sci. Soc. of Amer. Proc. 24: 265-268.

Bayne D.A. (1975). Revegetation of tailings areas at vacated mines near Carcross, Yukon Territory. Report submitted to K. Gullen, Water Resources Section, Dept. of Indian and Northern Affairs, Whitehorse, Y.T., 16 pp.

Berry, C.R. and D.H. Marx (1977). Growth of loblolly pine seedlings in strip-mined in koalin spoil as influenced by sewage sludge. J. Environ. Qual. 6 (4): 379-381.

Bowen, H.J. (1966). Trace Elements in Biochemistry. Academic Press, New York, pp. 25-11, 111-115, 173-210.

Bradshaw, A.D., M.O. Humphreys and M.S. Johnson (1978) The value of heavy metal tolerance on the revegetation of metalliferous mine wastes. In: Goodman, G.T. and M.J. Chadwick (eds.) Environmental Management of Mineral Wastes, Sijthoff and Noordhoff, The Netherlands, pp. 311-334.

Bremmer, J.M. (1960). Determination of nitrogen in soil by the Kjeldahl method. J. Agr. Sci. 55: 1-23

Bridges, E.M. (1970) World Soils. Cambridge University Press, London, 89 pp.

Brown, R.W. and R.S. Johnson (1976). Revegetation of an alpine mine disturbance: Beartooth Plateau, Montana. U.S.D.A. Forest Service Research Note INT-206, 8 pp.

Buckman, H. and N.C. Brady (1970). The Nature and Properties of Soils. Collier-MacMillan Canada, Ltd., Toronto (7th ed.), 653 pp.

Canadian Land Reclamation Association (1979). Proc. Canadian Land Reclamation Association, Fourth Annual Meting, Regina, 283 pp.

Chapma, H.D. (ed.) (1966). Diagnostic Criteria for Plants and Soils. Quality Printing Co., Inc., Abilene, Texas, 793 pp.

Coleman, M.T. and G.W. Thomas (1967). The basic chemistry of soil acidity. In: Pearson, R.W. and F. Adams (eds.) Soil Acidity and Liming. Amer. Soc. Agronomy Publ., Madison, Wisconsin, Agronomy No. 12, pp 1-42.

Cox, R.M. and T.C. Hutchinson (1979). Metal co-tolerance in the grass Deschampsia cespitosa. Nature 279 (5710): 231-233.

Cox, R.M. and T.C. Hutchinson (1980). Multiple metal tolerances and co-tolerances in the grass Deschampsia cespitosa from the Sudbury smelting area. New Phytol. 84: 631-646.

Cox, R.M. and T.C. Hutchinson (1981). Environmental factors influencing the rate of spread of the grass Deschampsia cespitosa invading areas around the Sudbury nickel-copper smelters. Water, Air and Soil Pollut. 16: 83-106.

Dabbs, D.L. (1974). Rationale and problems in the use of native pioneer species in land reclamation. In: Hocking, D. and W.R. McDonald (eds.) Proc. Workshop on Reclamation of Disturbed Lands in Alberta, Northern Forest Research Centre, Edmonton, Information Report NOR-X-116, pp. 82-87.

Day, A.D., K.L. Ludeke and T.C. Tucker (1977). Influence of soil materials in copper mine wastes on the growth and quality of barley grain. J. Environ. Qual. 6 (2): 179-181.

Delwiche, C.C. (1970). The nitrogen cycle. In: The Biosphere, W.H. Freeman and Co., San Francisco, pp. 69-80.

Emanual, D.M. (1976) Hydromulch: A potential use for hardwood bark residue. U.S.D.A. Forest Service Research Note NE-226, 3 pp.

Gemmell, R.P. (1977) Colonization of Industrial Wasteland. Edward Arnold (Publ.) Ltd., London, 75 pp.

Gizyn, W. (1980). Influence of bituminous shale fires on air and soil chemistry in the arctic. M.Sc. Thesis, University of Toronto.

Goodman, G.T., C.E. Pitcairn and R.P. Gemmell (1973). Ecological factors affecting growth on sites contaminated with heavy metals. In: Hutnik, R.J. and G. Davis (eds.). Ecology and Reclamation of Devastated Land, Gordon and Breach Sci. Publ. Inc., New York, Vol. II, pp. 149-173.

Grime, J.P. (1973a). Competitive exclusion in herbaceous vegetation. Nature 244 (5396): 344-347.

Grime, J.P. (1973b). Competition and diversity in herbaceous vegetation. Nature 244 (5414): 310-311.

Grime J.P. (1974). Vegetation classification by reference to strategies. Nature 250 (5461): 26-31.

Hardy, R.M. (1977). Requirements for development of a rehabilitation plan - Clinton Creek Mines, Cassiar Asbestos Corporation Report, prepared for Yukon Territory Water Board by R.M. Hardy and Associates Ltd., Calgary.

Harris, M.M. and M.F. Jurgensen (1977). Development of Salix and Populus mycorrhizae in metallic mine tailings. Plant and Soil 47: 509-517.

Heede, B.H. (1975). Submerged burlap strips aided rehabilitation of disturbed semi-arid sites in Colorado and New Mexico. U.S.D.A. Forest Service Research Note RM-302, 8 pp.

Hernandez, H. (1972). Surficial disturbance and natural plant recolonization in the Mackenzie delta region. In: Bliss L.C. and R.W. Wein (eds.) Botanical studies of natural and man-modified habitats in the eastern Mackenzie delta region and the arctic islands, Arctic Land Use Research Programme, D.I.A.N.A., Ottawa, A.L.U.R. 71-72-14, pp. 143-174.

Hernandez H. (1973). Natural plant recolonization of surficial disturbances, Tuktoyaktuk peninsula region, N.W.T. Can. J. Bot. 51: 2177-2196.

Hewitt, E.J. (1948). Relation of manganese and some other metals to iron deficiency in plants. Nature 161: 489.

Hutchinson, T.C. and L.M. Whitby (1974). A study of airborne contamination of the vegetaion and soils by heavy metals from te Sudbury, Ontario, copper-nickel smelters. In: Hemphill, D.D. (ed.) Trace Substances in Environmental Health VII, A Symposium, University of Missouri, pp 175-178.

Hutchinson, T.C. and L.M. Whitby (1977). The effects of acid rainfall and heavy metal particulates on boreal forest ecosystem near the Sudbury smelting region of Canada. Water, Air and Soil Pollut. 7: 421-438.

Hutchinson, T.C., W. Gizyn, M. Havas, and V. Zobens (1978). The effect of long term lignite burns of arctic ecosystems at the Smoking Hills, N.W.T. In: Hemphill, D.D. (ed.) Trace Substances in Environmental Health, Vol 12, University of Missouri, pp 317-332.

Jackson, W.A. (1967). Physiological effects of soil acidity. In: Pearson, R.W., F. Adams and R.C. Dinauer (eds.) Soil Acidity and Liming, Amer. Soc. Agronomy, Publ. Madison, Wisconsin, pp. 43-124.

Johnson, L. and K. VanCleve (1976) Revegetation in arctic and subarctic North America - a literature review. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, CRREL Report 76-15, 28 pp.

Johnson, M.S., T. McNeilly and P.D. Putwain (1977). Revegetation of metalliferous mine spoils contaminated by lead and zinc. Environ. Pollut. 12: 261-277.

Klebesadel, L.J. (1965). Response of native bluejoint grass, Calamagrostis canadensis in subarctic Alaska to harvest schedules and fertilizers. In: Proc. IX International Grasslands Congress, pp. 1309-1314.

Klock, G.O., J.M. Geist and A.R. Tiedemann (1975). Response of orchardgrass to sulfur in sulfur-coated urea. U.S.D.A. Forest Service, Sulfur Institute Journal 11 (3-4): 4-8.

Knabe, W. (1965). Observations on world-wide efforts to reclaim industrial waste land. In: Goodman, G.T. (ed.) Proc. British Ecological Soc. Symp. 5, Blackwell, Oxford, pp. 263-296.

Kruckelmann, H.W. (1974). Effects of fertilizers, soils, soil tillage and plant species on the frequency of Endogone chlamydospores and mycorrhizal infection in arable soils. In: Endomycorrhizas: Proc. Symp. held at the University of Leeds, England, pp. 511-525.

Kuja, A. (1980). Revegetation of mine tailings using native species from disturbed sites in Northern Canada. M.Sc. Thesis. Dept. fo Botany, University of Toronto, 242 pp.

Laidlaw, T.F. (1974). The potential of trembling aspen for reclamation planting in Alberta: some techniques of propagation. In: Hocking, D. and W.R. MacDonald (eds.) Proc. Workshop on Reclamation of Disturbed Land in Alberta, Northern Forest Research Centre Information Report NOR-X-116, Edmonton, pp 89-92.

Laughlin, W.N., P.F. Martin and G.R. Smith (1973). Nitrogen fertilization of polar bromegrass. Agroborealis 5(1): 12.

Lesko, G.L., H.M. Etter and T.M. Dillon (1975). Species selection, seedlings establishment and early growth on coal mine spoils at Luscar, Alberta. Northern Forest Research Centre, Canadian Forestry Service, Environment Canada, Edmonton. Information Report NOR-X-117, 37 pp.

Lundberg, P.E., O.L. Bennett and E.L. Mathias (1977). Tolerance of Bermudagrass selections to acidity. 1. Effects of lime on plant growth and mine spoil material. Agronomy J. 69: 913-916.

Marshall, I.B. (1979). The ecology and reclamation of lands disturbed by mining - a selected bibliography of Canadian references. Lands Directorate. Environment Canada. Occasional Paper 17, 94 pp.

Marx, D.H., W.C. Bryan and C.B. Davey (1970). Influence of temperature on aseptic synthesis of ectomycorrhizae by Thelephora terrestris and Pisolithus tinctorius on loblolly pine. Science 16: 424-431.

McCown, B.H. (1972). The influence of soil temperature on plant growth and survival in Alaska. In: Science in Alaska, Proc. of 23rd. Alaska Sci. Conf., Fairbanks, pp. 115-116.

McCown, B.H. (1973). Growth and survival of northern plants at low soil temperatures. Growth response, organic nutrients and ammonia utilization. U.S. Army Cold Regions Research and Engineering Laboratory, New Hampshire, Special Report 186, 15 pp.

Michelutti, R.E. (1974) How to establish vegetation on high iron-sulfur mine tailings. Can. Mining J. 95 (10): 54-58

Miller, G. (1978). A method of establishing vegetation on disturbed sites consistent with the theory of nucleation. In: Proc. Can. Land Reclamation Assoc., 3rd Annual Meeting, Sudbury, pp. 322-327.

Mitchell, W.W. (1974). Native bluejoint: a valuable forage and germ plasm resource. Agroborealis 6 (1): 21-22.

Murray, D.R. (1971). Factors affecting revegetation on uranium mine tailings in the Elliot Lake area - Part 1, physical conditions. Canadian Dept. of Energy, Mines and Resources, Mines Branch, Ottawa, Mining Research Centre, Internal Report MR7-104-1D, 12 pp.

Murray, D.R. (1974) Inventory of Canadian revegetation practice. Supplement 10-1 of the C.A.N.M.E.T. Pit Slope Manual, Department of Energy, Mines and Resources, Ottawa.

Murray, D.R. and Moffett (1977). Vegetating the uranium mine tailings at Elliot Lake, Ontario. J. Soil Water Conserv. 32: 171-174.

Ogram, D.G. and W.W. Fraser (1978). Reclamation of high sulfide tailings at Hudson Bay Mining and Smelting, Flin Flon, Manitoba. Reclamation Review 1 (1): 19-25.

Peterson, H.B. and R.F. Nielson (1973). Toxicities and deficiencies in mine tailings. In: Hutnick, R.J. and G. Davis (eds.) Ecology and Reclamation of Devastated Land. Gordon and Breach Sci. Publ., Inc., New York., Vol I, pp. 15-25.

Peterson, E.B. and N.M. Peterson (1977). Revegetation information applicable to mining sites in northern Canada. Western Ecological Services Ltd., Edmonton, 420 pp.

Pionke, H.B. and A.S. Rogowski (1969). How effective is the deep placement of acid spoil materials. In: Proc. Canadian Land Reclamation Assoc. 4th Annual Meeting, Regina, pp. 87-104.

Pitcairn, C.E.R. (1969). An ecological study of the factors influencing revegetation of industrial waste heaps contaminated with heavy metals. Ph.D. Dissertation, Swansea College, University of Wales, 240 pp.

Rorison, I.H. (1972). The effect of extreme soil acidity on the nutrient uptake and physiology of plants. In: Dost, H. (ed.) International Institute for Land Reclamation and Improvement, Symposium on Acid Sulphate Soils, Wageningen. Publ. 18, Vol I, pp. 223-251.

Sheldon, J.C. and A.D. Bradshaw (1976) The reclamation of slate waste tips by tree planting. Landscape Design 113: 31-33.

Smith, R.A.H. and A.D. Bradshaw (1972). Stabilization of toxic mine wastes by the use of tolerant plant populations. Extract from Transactions, Section A of the Institution of Mining and Metallurgy 81: A230-237.

Stover, J.C. (1973). Mulching in Alaska. In: 1973 Alaska Revegetation Workshop Notes, Co-operative Extension Service, University of Alaska, pp. 27-33.

Sutton, R.K. (1975). Why native plants aren't used more. J. Soil Water Conserv. 30: 240-242.

Turner, R.G. (1968). Heavy metal tolerance in plants. In: British Ecological Soc. Symp. No. 9, pp. 399-410.

Walton, H.F. (1973). Chelation. In: Chemistry in the Environment. Readings from Scientific American. W.M. Freeman and Co., San Francisco, pp. 344-348.

Watanabe, F.S. and S.R. Olsen (1962). Colorimetric determination of phosphate in water extracts of soil. Soil Sci. 93: 183-188.

Watkin, E.M. (1978). Practical and economic aspects of acid sulfide tailings reclamation. In: Proc. Canadian Land Reclamation Assoc., 3rd Annual Meeting, Sudbury, p. 120.

Weston, S. (1973). Report on developments and progress in reclaiming waste dumps and tailings ponds. Western Miner 46 (8): 29-37.

Wielgolaski, F.E. (1975). Primary production of tundra. In: Cooper, J.P. (ed.) Photosynthesis and Productivity in Different Environments. Cambridge University Press, London, pp. 75-106.

Wilkins, D.A. (1957). A technique for the measurement of lead tolerance in plants. Nature 180: 37-38.

Yarranton, G.A. and R.G. Morrison (1975). Spatial dynamics of a primary succession: nucleation. J. Ecology 62: 417-428.

Yorath, C.J., H.R. Balkwill and R.W. Klassen (1975). Franklin Bay and Malloch Hill Map Areas, District of MacKenzie (95 C, F). Energy, Mines and Resources, Canada. Geological Survey Paper 74-36, pp. 9, 14-16.

Younkin, W.E. (1973). Autecological studies of native species potentially useful for revegetation, Tuktoyaktuk region, N.W.T. In: Bliss, L.C. (ed.) Botanical studies of natural and man-modified habitats in the Mackenzie Valley, eastern Mackenzie delta region and the arctic islands. Arctic Land Use Research Programme, D.I.A.N.A. Alur 72-73-14, and Envir-social committee Northern Pipelines Task Force on northern oil development report 73-74, pp. 45-76.

Zsuffa, L. (1971). A rapid method for vegatative propagation of aspens and their hybrids. Forestry Chronicle 47: 36-39.

Table 1. Location and description of tailing sites in the Yukon, N.W.T. and Ontario.

| Tailing site | Location | Grid Reference | Status | Tailings Area |
|---|---|---|---|---|
| Whitehorse Copper Mines Ltd. | Yukon, 12 km south of Whitehorse | 60°38'N., 135°03'W | active since 1956 | 160 - 200 ha (1978) |
| United Keno Hill Mines Ltd. | Yukon, 48 km N.E. of Mayo | 64°N, 135°W | active | 67 ha (1978) |
| Cyprus Anvil Mining Corp. | Yukon, Faro, 400 km N.E. of Whitehorse | 62°22'N, 134°35'W | active since 1968 | 250 - 280 ha (1978) |
| Arctic Gold and Silver | Yukon, Carcross | 60°08'N, 134°43'W | abandoned | 1 ha |
| Venus | Yukon, 28 km south of Carcross | 60°03'N, 134°35'W | abandoned | 1 ha |
| Pine Point Mines Ltd. | N.W.T., 80 km east of Hay River | 61°N, 115°W | active | 3 sq km (1978) |
| Canada Tungsten Mining Corp. Ltd. | N.W.T., 200 km north of Watson Lake | 60°N, 128°W | active since | 10 ha (1978) |
| Nickel Rim - purchased by Falconbridge Nickel Ltd. | Ontario, MaClennan Twp. 12 km north of Falconbridge | 46°40'N, 80°48'W | abandoned; operated by Nickel Rim Mines 1952-1958 | 14 ha |

Table 2. Combinations of species and amendments used in plots established in 1977 on tailings. W = Whitehorse Copper tailings (July 14); V = Venus tailings (July 15); A = Arctic Gold & Silver tailings (July 16) and Cyprus Anvil tailings (July 20). There were two replicate plots per combination. Sawdust mulch was applied to one of each pair of seeded plots. Fertilizer treatments given as % total N - % $P_2O_5$ - % $K_2O$.

| | Stratified Seeds | | | Transplanted Clonal Material | | | | |
|---|---|---|---|---|---|---|---|---|
| Amendment | *Deschampsia cespitosa* | *Hordeum jubatum* | *Agrostis stolonifera* | *Artemesia tilesii* | *Arctagrostis latifolia* | *Carex bigelowii* | *Hierchloe alpina* | Local species |
| Unamended | W V A | W V A | | W V A | W V A | W V A | W V A | W V A |
| Inorganic fert. (21-7-14) | W V | W V | | | | | | |
| Inorganic fert. (10-20-10) | W V | W V | | | | | | |
| Organic fert. (6-8-6) | W V | W V | | | | | | |
| Sulphur-coated urea (32-0-0) | W V | W V | | | | | | |
| Peat only | W V A | W V A | | W V A | W V A | W V A | W V A | W V |
| Limestone only | A | A | | A | A | A | A | A |
| Limestone + 6-8-6 | A | A | | A | A | A | A | |
| Limestone + peat | A | A | A | A | A | A | A | A |
| Peat + 21-7-14 | W V | W V | | W | W | W | W | W |
| Peat + 10-20-10 | W V | W V | | W | W | W | W | W |
| Peat + 6-8-6 | W V | W V | | W V | W V | W V | W V | W V |
| Peat + 32-0-0 | W V | W V | | W V | W V | W V | W V | W |
| Limestone + peat + 6-8-6 | A | A | A | A | A | A | A | A |

Table 3. Combinations of species and amendments used in plots established in 1978 on tailings. Tailings sites: N = Nickel Rim (May 10), A = Arctic Gold and Silver (June 6), C = Cyprus Anvil (June 15), V = Venus (12 June) and W = Whitehorse Copper (June 14). There were two replicate plots at Venus, one on dry tailings, the other on moist tailings. Fertilizer treatments given as % total N - % $P_2O_5$ - % $K_2O$.

| Amendment | Seeds | | | | | | | | Transplants | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Deschampsia cespitosa* | | | | | *Hordeum jubatum* | | | | | *Arctagrostis latifolia* | | Local species | |
| Unamended | N | A | C | W | V | | A | C | W | V | A | V | A | C W V |
| Inorganic fert. (21-7-14) | N | | | W | V | | | | W | V | | | | |
| Inorganic fert. (10-20-10) | N | | | W | V | | | | W | V | | | | |
| Organic fert.(6-8-6) | N | | | W | V | | | | W | V | V | | W | V |
| Sulphur-coated urea (32-0-0) | N | | | W | V | | | | W | V | V | | W | V |
| Peat only | | A | C | W | V | | A | C | W | V | A | V | W | V |
| P + 21-7-14 | | | | W | V | | | | W | V | | | | |
| P + 10-20-10 | | | | W | V | | | | W | V | | | | |
| P + 6-8-6 | | | | W | V | | | | W | V | V | | W | V |
| P + 32-0-0 | | | | W | V | | | | W | V | V | | W | V |
| P + 6-8-6 (high rate) | | | | | V | | | | | | | | | |
| P + 32-0-0 (high rate) | | | | | V | | | | | | | | | |
| Limestone only | N | A | C | | | | A | C | | | A | | A | C |
| L + 6-8-6 | N | A | C | | | | A | C | | | A | | A | C |
| L + 21-7-14 | N | A | C | | | | | | | | A | | A | |
| L + 10-20-10 | N | A | C | | | | | | | | A | | A | |
| L + 32-0-0 | N | A | C | | | | | | | | A | | A | |
| Lime + Peat | | A | C | | | | A | C | | | A | | A | C |
| L + P + 6-8-6 | | A | C | | | | A | C | | | A | | A | C |
| L + P + 21-7-14 | | A | C | | | | | | | | A | | A | |
| L + P + 10-20-10 | | A | C | | | | | | | | A | | A | |
| L + P + 32-0-0 | | A | C | | | | | | | | A | | A | |
| L + 6-8-6 (high rate) | N | | | | | | | | | | | | | |
| L + 32-0-0 (high rate) | N | | | | | | | | | | | | | |

Table 4. Measurements of pH, conductivity, bulk density, loss on ignition, particle size fractions and macronutrient concentrations for the tailings studied and a garden soil. Macronutrient concentrations given in ug $g^{-1}$.

| | Arctic Gold and Silver | Cyprus Anvil (old tailings) | Cyprus Anvil (new tailings) | Nickel Rim | Venus | Whitehorse Copper | Garden Soil[a] |
|---|---|---|---|---|---|---|---|
| pH range | 1.8 - 2.1 | 2.3 - 2.9 | 3.0 - 4.0 | 3.0 - 3.3 | 7.0 - 7.1 | 8.9 - 9.1 | 7.0 - 7.5 |
| Conductivity (mmhos 18°C) | 12.4 ± 0.14[b] | 106.0 ± 4.0 | 3.4 ± 0.4 | 9.0 ± 0.2 | 2.1 ± 0.3 | 0.8 ± 0.14 | 0.03 ± 0.01 |
| Density ($g\ cm^{-3}$) | 1.43 | 1.57 | 2.27 | 1.50 | 1.67 | 1.75 | 1.15 |
| Ignition (% dry wt.) | 1.60 ± 0.25 | 2.40 ± 0.25 | 0.13 ± 0.08 | 1.14 ± 0.14 | 0.49 ± 0.05 | 0.13 ± 0.08 | 13.0 ± 0.7 |
| Particle Size Fraction (%) | | | | | | | |
| clay-silt | 33 ± 2 | 13 ± 0.4 | 4 ± 0.2 | 5 ± 1 | 12 ± 5 | 23 ± 4 | - |
| fine sand | 60 ± 2 | 75 ± 9 | 91 ± 5 | 62 ± 6 | 74 ± 5 | 69 ± 5 | - |
| coarse sand | 7 ± 1 | 12 ± 5 | 5 ± 0.6 | 33 ± 6 | 14 ± 2 | 8 ± 1 | - |
| N | nd[c] | 150 ± 110 | 160 ± 71 | 480 ± 370 | 140 ± 100 | 360 ± 110 | 200 - 5000 |
| P | 30 ± 15 | 66 ± 14 | 8 ± 4 | 60 ± 35 | 71 ± 42 | 120 ± 2 | 100 - 2000 |
| K | 22000 ± 4000 | 2040 ± 350 | 160 ± 112 | 4500 ± 290 | 8400 ± 90 | 5550 ± 685 | 400 - 30000 |
| Ca | 2060 ± 520 | 1500 ± 470 | 318 ± 135 | 49000 ± 3300 | 5500 ± 920 | 87000 ± 28000 | 7000 - 36000 |
| Mg | 5900 ± 1900 | 1550 ± 330 | 670 ± 580 | 43000 ± 3500 | 9700 ± 710 | 87000 ± 25000 | 1200 - 15000 |
| S[d] | $2.0 \times 10^4$ | $32.5 \times 10^4$ | $44.4 \times 10^4$ | 9000 | $13.5 \times 10^4$ | 6000 | 100 - 2000 |
| $SO_4$ | 110000 ± 1000 | 24000 ± 3000 | 5200 ± 300 | 2100 ± 100 | 8000 ± 2000 | 1000 ± 80 | - |
| Ca:Mg | 0.35 | 0.97 | 0.47 | 1.14 | 0.88 | 1.0 | 1.0 |

[a] expected range for general surface soil for N, P, K, Ca, Mg, S, and Ca:Mg; [b] ± standard deviation
[c] not detectable; [d] total sulphur determined for single samples using LECO induction furnace

Table 5. Total concentrations of heavy metals and other potentially phytotoxic elements in the tailings studied. Concentrations are given in ug $g^{-1}$ (mean ± standard deviation). Tailings are in order of increasing pH.

| Element | Arctic Gold and Silver | Cyprus Anvil (old tailings) | Cyprus Anvil (fresh tailings) | Nickel Rim | Venus | Whitehorse Copper | Mineral Soil* |
|---|---|---|---|---|---|---|---|
| Ag | nd | nd | nd | nd | nd | nd | 0.01 - 5 |
| Al | 32000 ± 1300 | 7100 ± 1100 | 860 ± 80 | 51000 ± 2600 | 26900 ± 500 | 17000 ± 9000 | 1 - 300000 |
| As | 5220 ± 305 | 388 ± 14 | 400 ± 19 | nd | 50200 ± 3400 | 15 ± 4 | 0.1 - 40 |
| Ba | 654 ± 346 | 52700 ± 5300 | 650 ± 84 | nd | nd | nd | 100 - 3000 |
| Br | nd | nd | nd | 400 ± 286 | nd | nd | 1 - 10 |
| Cd | 18 ± 1 | 10 ± 1 | 15 ± 3 | 0.4 ± 0.2 | 114 ± 2 | 0.7 ± 0.1 | 0.01 - 0.7 |
| Cl | nd | nd | nd | nd | nd | nd | 10 - 10000 |
| Co | nd | 61 ± 8 | 86 ± 5 | 7 ± 9 | nd | 22 ± 2 | 1 - 40 |
| Cu | 140 ± 12 | 716 ± 75 | 613 ± 79 | 392 ± 21 | 330 ± 82 | 1710 ± 72 | 2 - 100 |
| Fe | 13000 ± 6000 | 154000 ± 54000 | 149000 ± 41000 | 100000 ± 32000 | 105000 ± 9500 | 162000 ± 8000 | 5000 - 50000 |
| Mn | 152 ± 12 | 189 ± 33 | 180 ± 28 | 1030 ± 30 | 489 ± 33 | 830 ± 17 | 100 - 10000 |
| Na | 540 ± 17 | 159 ± 35 | 50 ± 11 | 12000 ± 3000 | 753 ± 37 | 3400 ± 540 | 750 - 7500 |
| Ni | 13 ± 2 | 23 ± 8 | 14 ± [illegible] | 290 ± 10 | 20 ± 3 | 21 ± 2 | 10 - [illegible]000 |
| Pb | 952 ± 254 | 102 ± 41 | 130 ± 31 | 18 ± 4 | 2300 ± 970 | 9 ± 4 | 2 - 200 |
| U | 8 ± 3 | 2 ± 0.2 | 0.7 ± 0.1 | 1.3 ± 1.7 | 76 ± 39 | 2 ± 0.7 | 0.9 - 9 |
| V | 8 ± 6 | 17 ± 3 | 5 ± 0.4 | 200 ± 20 | 34 ± 1 | 71 ± 30 | 20 - 500 |
| W | 32 ± 10 | nd | nd | nd | 96 ± 35 | 25 ± 6 | 1 - 2 |
| Zn | 2440 ± 590 | 4700 ± 1570 | 9630 ± 460 | 291 ± 403 | 18300 ± 1700 | 178 ± 110 | 10 - 300 |

* expected range for mineral surface soils (Bowen 1966; Buckman and Brady 1970)

Table 6. Concentrations of Pb, Zn, Cd, Cu, Ni and As in shoots and roots of six test species grown in the glashouse on unamended tailings from Arctic Gold and Silver, Cyprus Anvil, Nickel Rim, Venus and Whitehorse Copper.

| | Pb | | Zn | | Cd | | Cu | | Ni | | As | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | shoot | root | shoot | root | shoot | root | shoot | root | shoot | root | shoot | root |
| **Artemisia tilesii** | | | | | | | | | | | | |
| Arctic G&S | 107 | 535 | 1020 | 1530 | 20 | 19 | 95 | 273 | 45 | 155 | 5220 | 2740 |
| Cyp. Anv. old | 147 | 1750 | 10600 | 15100 | 14 | 19 | 494 | 867 | 21 | 40 | nd* | nd |
| Cyp. Anv. new | 105 | 922 | 12900 | 18500 | 64 | 34 | 729 | 1150 | 12 | 22 | nd | nd |
| Nickel Rim | 17 | 53 | 430 | 737 | 1.3 | 0.3 | 60 | 265 | 439 | 566 | nd | nd |
| Venus | 84 | 451 | 300 | 1080 | 17 | 15 | 11 | 27 | 27 | 97 | 2990 | 7600 |
| Whitehorse Cu | 19 | 42 | 66 | 83 | 0.1 | 6.5 | 87 | 586 | 15 | 65 | nd | nd |
| Gard. Soil | 15 | 16 | 81 | 134 | 0.5 | 1 | 13 | 19 | 24 | 20 | nd | nd |
| Seed Mix | 21 | 27 | 85 | 244 | 0.3 | 1.7 | 9 | 19 | 36 | 21 | nd | nd |
| **Arctagrostis latifolia** | | | | | | | | | | | | |
| Arctic G&S | 125 | 700 | 984 | 817 | 17 | 11 | 151 | 177 | 36 | 33 | 4910 | 2990 |
| Cyp. Anv. old | 272 | 4540 | 8340 | 7280 | 11 | 15 | 373 | 689 | 56 | 93 | nd | nd |
| Cyp. Anv. new | 239 | 2220 | 12700 | 6700 | 31 | 18 | 400 | 1030 | 22 | 47 | nd | nd |
| Venus | 71 | 1540 | 291 | 1860 | 6 | 50 | 14 | 57 | 15 | 88 | 277 | 55400 |
| Whitehorse Cu | 20 | 48 | 70 | 173 | 0.4 | 2.3 | 68 | 548 | 26 | 51 | nd | nd |
| Gard. Soil | 9 | 24 | 70 | 163 | 0.1 | 2.3 | 12 | 30 | 20 | 47 | nd | nd |
| Seed. Mix | 15 | 32 | 66 | 154 | 0.4 | 1.7 | 13 | 26 | 26 | 41 | nd | nd |
| **Deschampsia cespitosa** | | | | | | | | | | | | |
| Arctic G&S | 102 | 631 | 489 | 703 | 11 | 11 | 124 | 174 | 30 | 29 | 3410 | 10200 |
| Cyp. Anv. old | 254 | 4770 | 6500 | 8800 | 9 | 10 | 2324 | 724 | 13 | 23 | nd | nd |
| Cyp. Anv. new | 64 | 525 | 8870 | 11500 | 19 | 24 | 262 | 1260 | 26 | 31 | nd | nd |
| Nickel Rim | 21 | 50 | 220 | 379 | 0.5 | 1.5 | 57 | 196 | 197 | 310 | nd | nd |
| Venus | 72 | 1740 | 353 | 1630 | 7 | 61 | 13 | 54 | 18 | 29 | 359 | 7200 |
| Whitehorse Cu | 24 | 45 | 85 | 441 | 0.7 | 2.5 | 150 | 683 | 23 | 24 | nd | nd |
| Gard. Soil | 13 | 26 | 61 | 114 | 1 | 0.3 | 15 | 75 | 8 | 83 | nd | nd |
| Seed. Mix | 7 | 38 | 71 | 318 | 0.3 | 3 | 8 | 31 | 8 | 49 | nd | 12 |
| **Hordeum jubatum** | | | | | | | | | | | | |
| Arctic G&S | 92 | 350 | 809 | 602 | 19 | 14 | 176 | 170 | 38 | 39 | 3980 | 12400 |
| Cyp. Anv. old | 170 | 3100 | 7950 | 10650 | 11 | 10 | 424 | 574 | 13 | 17 | nd | nd |
| Cyp. Anv. new | 484 | 759 | 8300 | 13800 | 19 | 53 | 360 | 1000 | 6 | 41 | nd | nd |
| Nickel Rim | 31 | 45 | 270 | 336 | 2.3 | 2.3 | 87 | 119 | 392 | 490 | nd | nd |
| Venus | 162 | 663 | 324 | 1180 | 17 | 23 | 22 | 39 | 30 | 33 | 1970 | 16200 |
| Whitehorse Cu | 15 | 24 | 57 | 114 | 0.6 | 0.5 | 132 | 665 | 14 | 33 | nd | nd |
| Gard. Soil | 18 | 71 | 53 | 176 | 0.4 | 2 | 11 | 22 | 44 | 46 | nd | nd |
| Seed. Mix | 16 | 38 | 58 | 204 | 0.3 | 0.9 | 11 | 20 | 11 | 18 | nd | 2 |

* not detectable

Table 7. Concentrations of As, Cd, Cu, Ni, Pb and Zn in washed leaf and stem tissue of clonal material surviving on various amendments in the field. Plants were sampled two months after being transplanted to field plots at Arctic Gold and Silver, Venus and Whitehorse Copper tailings. Plants were sampled on the Nickel Rim tailings after one year. Concentrations were expressed as ug $g^{-1}$ dry weight. Fertilizer treatments are given as %N-%P-%K.

| Tailing Site | Species | Tissue | Amendment | As | Cd | Cu | Ni | Pb | Zn |
|---|---|---|---|---|---|---|---|---|---|
| Nickel Rim | Arctagrostis latifolia | leaf | unamended | nd* | 1 | 34 | 50 | 7 | 57 |
| | Carex bigelowii | leaf | unamended | nd | 3 | 134 | 200 | 22 | 168 |
| Arctic Gold and Silver | Arctagrostis latifolia | leaf | limestone | 5 | 4 | 19 | 18 | 10 | 153 |
| | | | lime + peat | 15 | 3 | 24 | 21 | 18 | 170 |
| | Artemisia tilesii | leaf | limestone | 3 | 13 | 39 | 32 | 21 | 193 |
| | Hordeum jubatum | leaf | unamended | 2320 | 6 | 58 | 5 | 13 | 260 |
| Venus | Arctagrostis latifolia | leaf | unamended | 64 | 10 | 16 | 9 | 19 | 308 |
| | | | peat | 180 | 8 | 16 | 9 | 18 | 249 |
| | Carex bigelowii | leaf | unamended | 48 | 4 | 19 | 27 | 29 | 245 |
| | Hordeum jubatum | leaf | unamended | 84 | 6 | 12 | 5 | 19 | 250 |
| | Salix planifolia | leaf | unamended | 28 | 6 | 12 | 5 | 23 | 181 |
| | Equisetum scirpoides | stem | unamended | 3900 | 4 | 14 | 1 | 130 | 485 |
| | Deschampsia cespitosa | leaf | unamended | 2100 | 63 | 54 | 27 | 1130 | 2800 |
| Whitehorse Copper | Arctagrostis latifolia | leaf | unamended | nd | T* | 248 | 25 | 5 | 61 |
| | | leaf | peat + 21-7-14 | nd | 3 | 367 | 18 | 5 | 50 |
| | | leaf | peat + 10-20-10 | nd | T | 245 | 9 | 5 | 49 |
| | | leaf | peat + 6-8-6 | nd | nd | 184 | 20 | 2 | 57 |
| | | leaf | peat + 32-0-0 | nd | T | 205 | 27 | 4 | 48 |
| | Artemisia tilesii | leaf | unamended | nd | 5 | 309 | 10 | 5 | 65 |
| | | leaf | peat + 21-7-14 | nd | 6 | 160 | 9 | 3 | 86 |
| | | leaf | peat + 10-20-10 | nd | 7 | 254 | 23 | 4 | 121 |
| | | stem | peat + 10-20-10 | nd | 3 | 119 | 32 | 1 | 29 |
| | | leaf | peat + 6-8-6 | nd | 3 | 272 | 36 | 6 | 146 |
| | | stem | peat + 6-8-6 | nd | 3 | 233 | 18 | 6 | 62 |
| | Carex bigelowii | leaf | unamended | nd | 2 | 232 | 28 | 4 | 64 |
| | | leaf | peat + 21-7-14 | nd | 2 | 311 | 35 | 5 | 64 |
| | | leaf | peat + 10-20-10 | nd | 3 | 435 | 26 | 5 | 95 |
| | | leaf | peat + 6-8-6 | nd | 2 | 286 | 27 | 3 | 55 |
| | | leaf | peat + 32-0-0 | nd | 4 | 369 | 35 | 4 | 59 |
| | Hierochloe alpina | leaf | unamended | nd | T | 475 | 26 | 6 | 47 |
| | | leaf | peat + 21-7-14 | nd | T | 412 | 55 | 6 | 37 |
| | | leaf | peat + 10-20-10 | nd | T | 388 | 10 | 4 | 79 |
| | | leaf | peat + 6-8-6 | nd | T | 336 | 27 | 3 | 47 |
| | | leaf | peat + 32-0-0 | nd | 1 | 399 | 6 | 5 | 55 |
| | Epilobium angustifolium | leaf | unamended | nd | nd | 157 | 5 | 3 | 24 |
| | | stem | unamended | nd | nd | 82 | 8 | 3 | 24 |
| | Hordeum jubatum | leaf | unamended | nd | T | 263 | 17 | 3 | 18 |

* nd = not dectable; T = trace

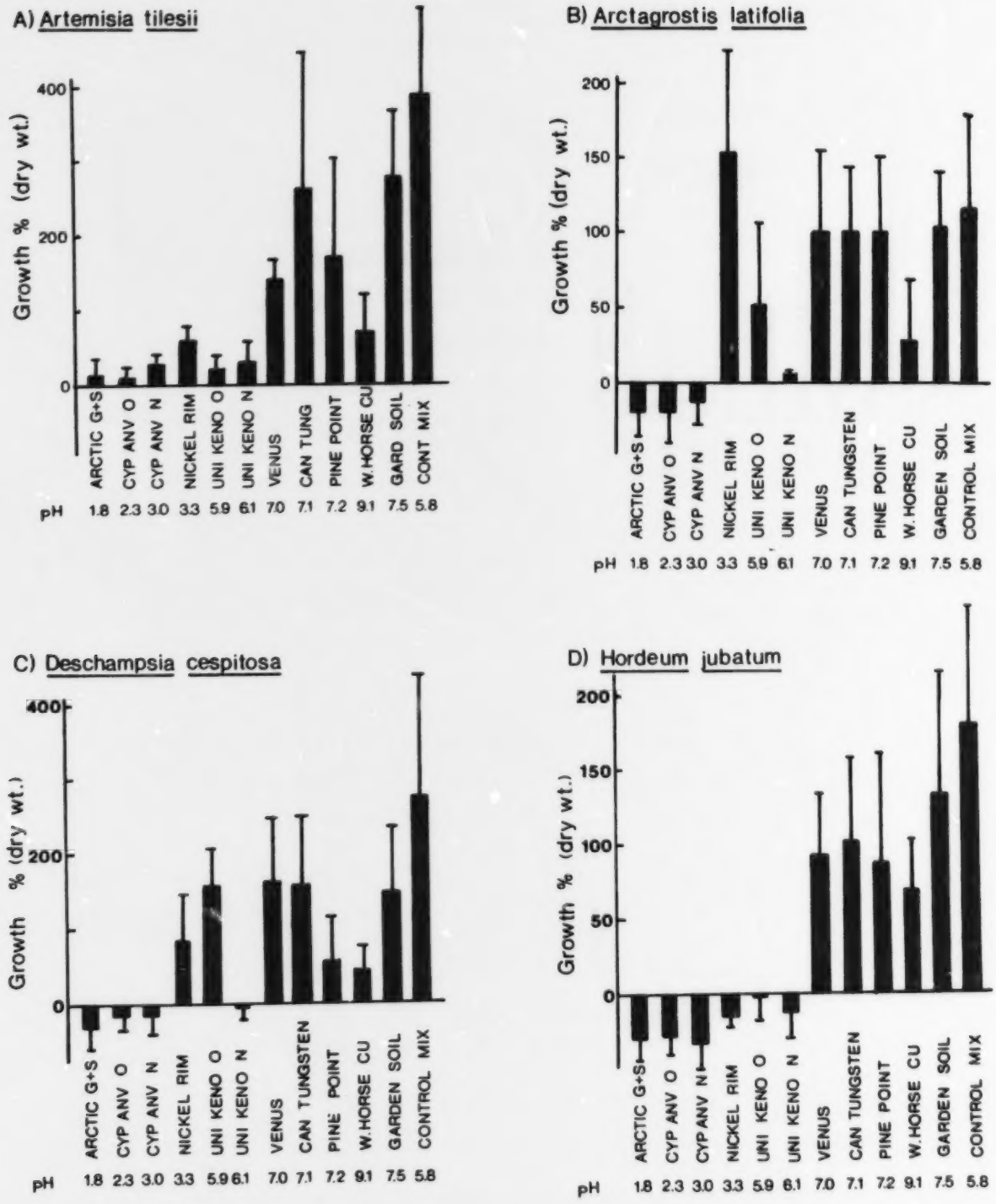


Figure 1. Growth response of (A) Artemisia tilesii, (B) Arctagrostis latifolia, (C) Deschampsia cespitosa seedlings, and (D) Hordeum jubatum seedlings grown on each of the unamended tailings and on control soils. Growth was measured as a net change in biomass as a percentage of the initial weight. Standard deviations are also given.

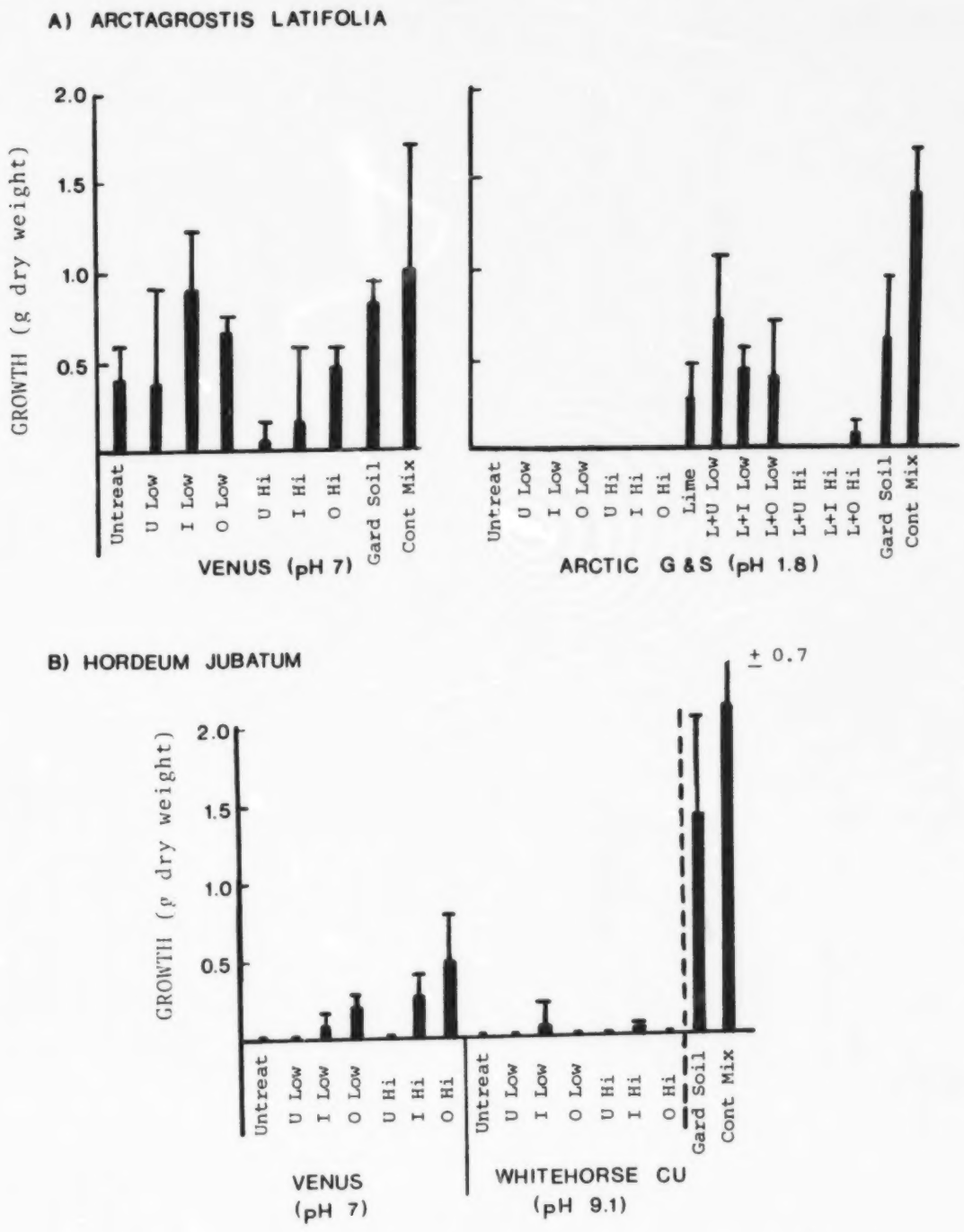


Figure 2. Growth response in grams dry weight of (A) four tillers of Arctagrostis latifolia grown in the glasshouse on amended tailings of Arctic Gold and Silver and Venus, and on control soils, and (B) four tillers of Hordeum jubatum grown in the glasshouse on unamended tailings of Venus and Whitehorse Copper, and on control soils. Amendments to tailings: U = 32-0-0 %NPK, I = 10-20-10 %NPK, O = 6-8-6 %NPK, L = Limestone added to raise the pH greater than 5.0. Fertilizer applications were Low (34 g $m^{-2}$) or high (Hi) (170 g $m^{-2}$).

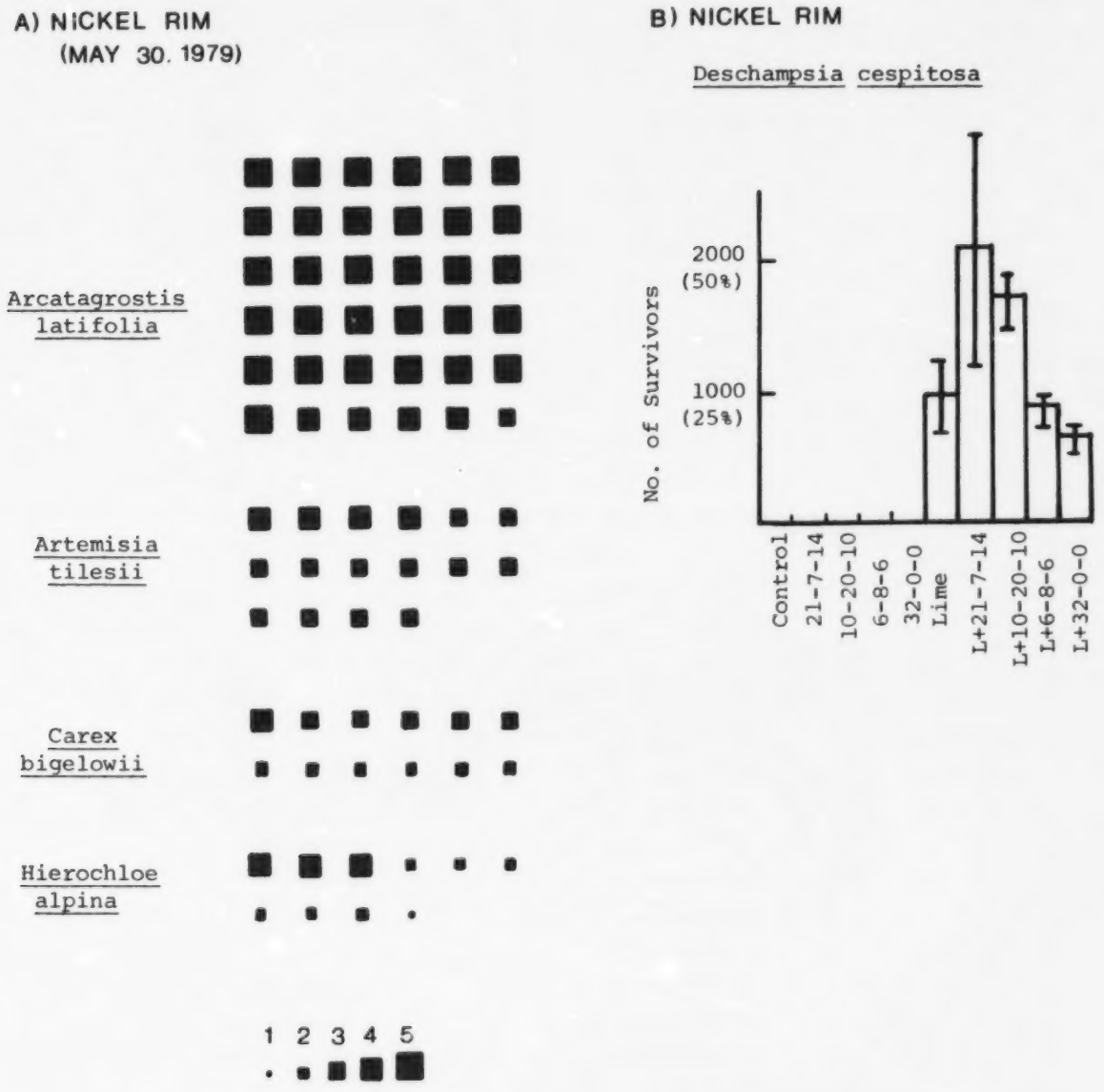


Figure 3. Responses of plants to Nickel Rim tailings. (A) A schematic representation of the relative vigor of clones transplanted from the Smoking Hills in Sept. 1976 to unamended tailings. The values 1-5 were based mainly on percentages of live shoots still remaining: 1 = less than 10%, 2 = 10-49%, 3 = 50-74%, 4 = 75-100%, 5 = +100%, representing lateral growth. (B) Seedling response as total number of survivors and survivorship as a percentage of total seedlings sown of Deschampsia cespitosa on amended tailings after on growing season (May-Sept. 1978). Amendments included: L = Limestone to raise pH to greater than 5.0, and fertilizer as %N-%P-%K.

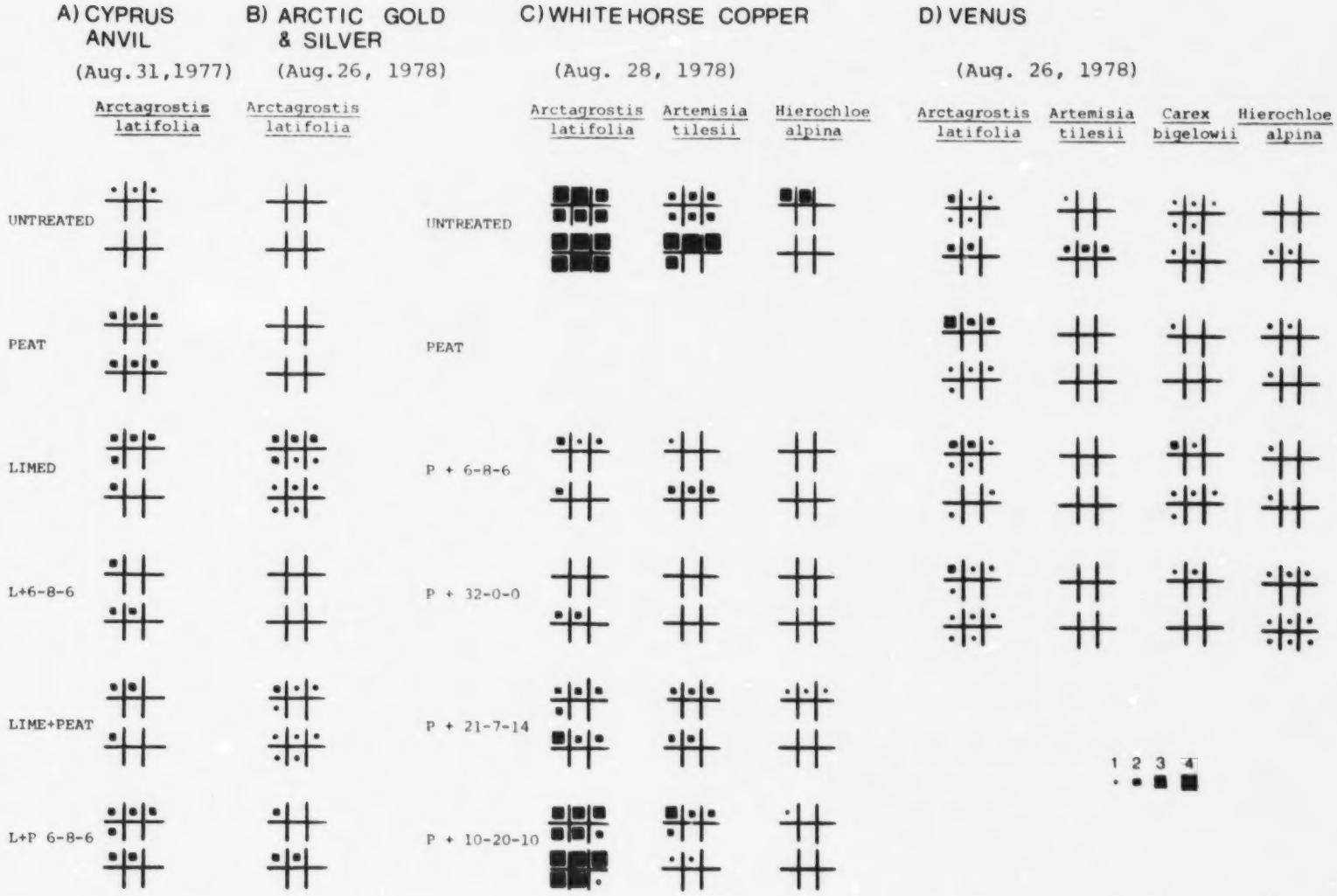


Figure 4. Schematic representations of the relative vigor of clones transplanted from the Smoking Hills to tailings at (A) Cyprus Anvil, (B) Arctic Gold and Silver, (C) Whitehorse Copper, and (D) Venus. The values 1-5 were based mainly on percentages of live shoots remaining: 1 = less than 10%, 2 = 10-49%, 3 = 50-74%, 4 = 75-100%, representing lateral growth.

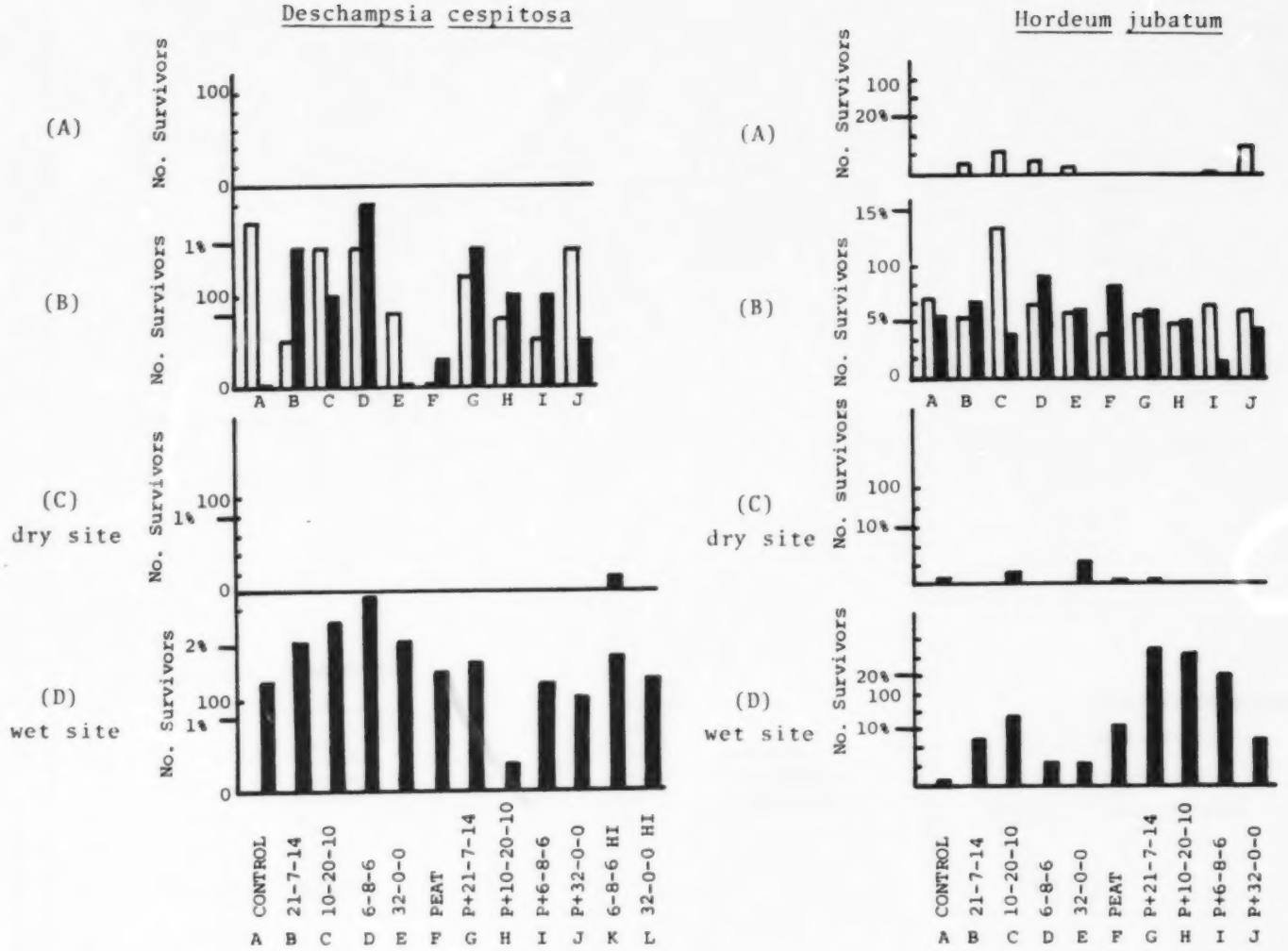


Figure 5. Seedling survivorship of Deschampsia cespitosa and Hordeum jubatum on tailing amendments at the Venus site. Plots seeded in July 1977 (A) were re-seeded in Sept. 1977 (B). Plots were also seeded on an area of dry tailings (C) and an area of wet tailings near a pond (D) in June 1978. Dark bars indicate unmulched plots; white bars indicate plots mulched with sawdust. Amendments included: P = Peat and fertilizer as %N-%P-%K.

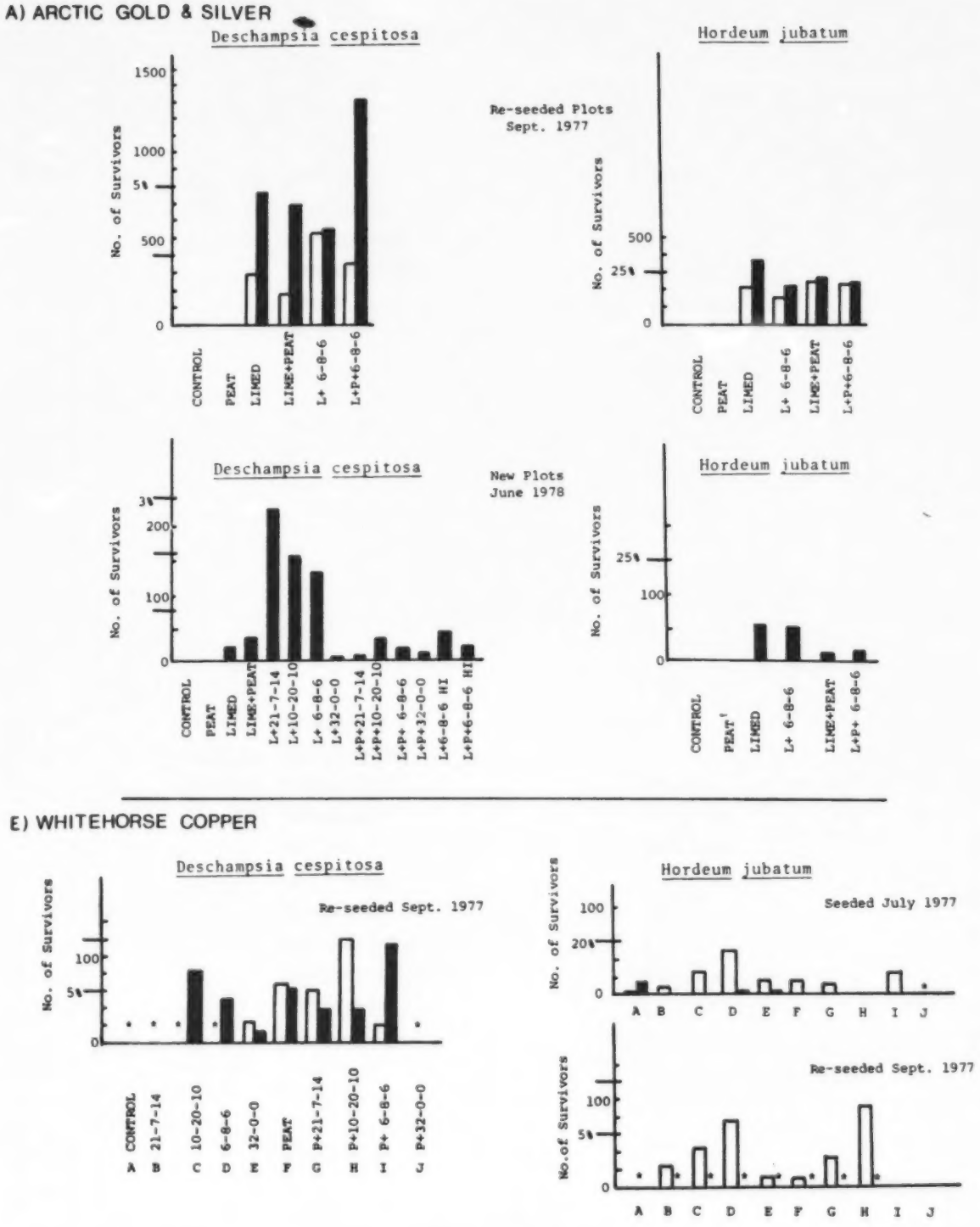


Figure 6. Seedling survivorship of Deschampsia cespitosa and Hordeum jubatum on tailing amendments at (A) Arctic Gold and Silver and (B) Whitehorse Copper. Time of seeding is indicated. Dark bars indicate unmulched plots; white bars indicate plots mulched with sawdust. Amendments included: L = Limestone, P = Peat, fertilizer as %N-%P-%K. Fertilizers were applied at either a low (34 g $m^{-2}$) or high (170 g $m^{-2}$) rate. * indicates plots washed out by tailing slurry.